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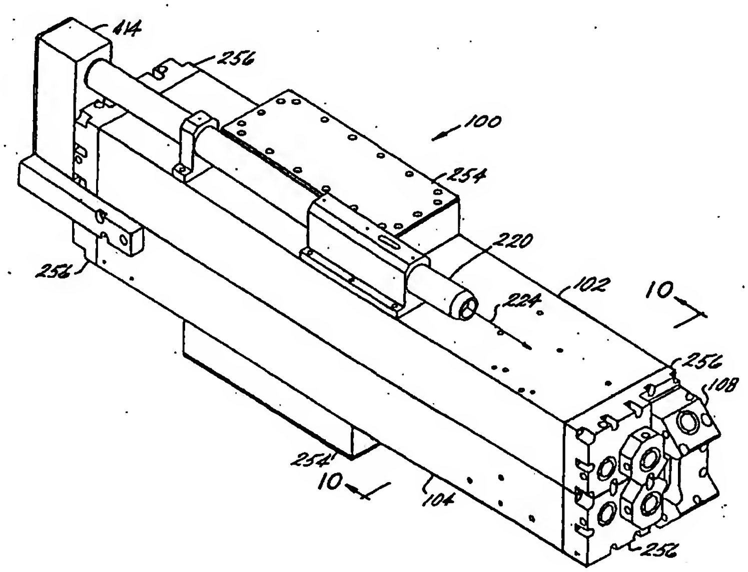
(54) Title: A METHOD AND APPARATUS FOR INCREASING THE POWER OF A WAVEGUIDE LASER



(57) Abstract: A laser (100) comprises a housing and a plurality of waveguides (102, 104) positioned within the housing, the waveguides (102, 104) defining a plurality of channels for guiding a laser beam (224). A laser system (100) comprises a housing, a plurality of waveguide lasers (102, 104), and a beam combiner for superimposing the output of the plurality of waveguide lasers (102, 104), the beam combiner disposed on the housing. A laser system (100) comprises a plurality of waveguide lasers (102, 104) and a beam combiner including a wavelength selective mirror for superimposing the output of the plurality of waveguide lasers (102, 104).

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A METHOD AND APPARATUS FOR INCREASING THE POWER OF A WAVEGUIDE LASER

BACKGROUND OF THE INVENTION

Field of the Invention

This invention relates to a method and system for increasing the output power of diffusion cooled waveguide lasers, and more particularly to increasing the output power of diffusion cooled CO_2 waveguide lasers.

Prior Art

A convenient and cost effective method of obtaining a higher power laser is to cascade two lasers into a single laser feedback cavity as schematically illustrated in prior art Figure 1 herein. Referring to Figure 1, if a first laser 2 has a nominal power output, P_1 of 100W and a second laser 4 a nominal power output, P_2 of 100W, then cascading the laser gain media as illustrated should yield a laser of 200W (i.e., $P_1 + P_2$) if the losses in the laser beam 6 making the transition from laser 2 to laser 4 and vise versa are sufficiently small. This approach provides a "quick-to-market" solution, saves research and development costs, reduces the number of inventory parts, and provides cost savings arising from a commonality of parts and an ease of mirror alignment. The approach of prior art Figure 1 has been extensity used with non-waveguide lasers. This approach has not been utilized to date with waveguide lasers because losses are believed to be too great.

Unfortunately, the end-to-end or in line cascading approach of prior art Figure 1 results in a laser head that is twice as long as the original laser. This increased length causes problems associated with increased vibration, frequency and pointing

sensitivities while it possesses an unsymmetric thermal cooling arrangement. Unsymmetric cooling is always undesirable because it causes bending and twisting of the long rectangular laser package which has undesirable effects on the laser output performance. The long resultant laser structure 2, 4 of prior art Figure 1 also makes this configuration unattractive for applications that require a more compact, rigid and rugged package such as for example, applications that require the laser to be placed on a moveable robotic arm or other periodically moving platform or in a high noise industrial environment.

The output power of a waveguide laser may be increased by combining the output of two linearly orthogonally polarized lasers to obtain a cross polarized laser beam of twice the output power. Some advantages in this scheme are similar to the in line cascading approach of Figure 1, namely, reduced parts inventory and thus inventory costs, savings by avoiding the development costs of a new laser of higher output power. For some applications, cross polarization has advantages over linearly polarized beams emitted by the arrangement of Figure 1. Polarization power-combining also provides a quick response to market needs by quickly expanding a laser product line to higher powers. The use of two high volume, and thus correspondingly low cost, lasers in either the cascading of two lasers or in a polarization power-combining approach can frequently result in a lower cost, high power laser than by scaling a lower power laser to a new, higher power laser design. This is especially true, if the sales volume of the higher power laser is considerably lower than the low power laser utilized in either end-to-end cascading or in the orthogonal the polarization power-combining schemes. Because of these advantages, both laser cascading and laser polarization power-combining techniques have been used in producing commercial lasers. The use of half wave plates for polarization rotating one of the laser beams by 90 degrees has been most often used in the past.

To achieve polarization power-combining, one must rotate the output of one of the horizontally polarized laser output beams by 90 degrees. Referring to prior art Figures 2A and 2B, two and three-mirror optical polarization rotators 8, 10 respectively are shown. Such polarization rotators are well known in the art. In both of the examples in Figure 2A and 2B, the incoming vertical polarized beams 8a, 10a is rotated 90 degrees so that the output beams 8b, 10b are horizontally polarized or vice versa.

Also, for the two-mirror polarization rotator 8 of Figure 2A, the output beam 8b is displaced 90 degrees upward and redirected sideways by 90 degrees, while for the three mirror-rotator 10 of Figure 2B, the output beam 10b is emitted parallel to the input beam 10a but displaced to the right and upward as shown. In power-combining lasers such beam translation and/or displacement are not usually desired nor tolerated.

The technology for three and four-mirror optical rotators that do not deviate the output beam from the propagation axis is available and well know in the art but have not been used previously with diffusion cooled waveguides nor in slab lasers. These devices do not have redirections or displacements of the output beams (Reflection Polarizers for Vacuum Ultraviolet Using Al+MgF_2 Mirrors and MgF_2 Plate, by G. Hass and W.R. Hunter; Applied Optics Vol. 17, January 1, 1978; R.N. Ham, R.A. MacRae and E.T. Arakawa; J. Opt. Soc. Am. 55, page 1460(1965); Reflective Device for polarization Rotation by Charles E. Greninger; Applied Optics, Vol. 27, No. 4, page 774, February 15, 1988 which are incorporated herein by reference). Such devices also have a high degree of linear polarization if one or more reflections occur at approximately Brewster's angle, θ_B. Designs are also available that take into account polarization effects resulting from dielectrically coated metal mirrors in order to obtain a high degree of polarization.

Referring to prior art Figures 3A, 3B, 4A and 4B, examples of three and four-mirror optical polarization rotators 12, 14 without overall beam deviation respectively are shown. The specific angles of incidents for the mirrors M_1, M_2, M_3, M_4 can be selected to maximize the degree of linear polarization based on the properties of the mirrors as is well known in the art. The four-mirror configuration of Figures 4A and 4B requires any two of its mirrors to have a quarter wave($\lambda/4$) thin film coating 14c deposited on its surface in order to obtain the 90 degree rotation. The three-mirror rotator does not require such a quarter wave coating and thus is preferred. Quarter wave coatings result in variations in the output performance because of sensitivities to wavelength and temperature changes. The three mirror arrangement enjoys a cost advantage (i.e., fewer mirrors and no requirement for quarter wave coating. However the three-mirror arrangement has a higher profile than the four-mirror rotator.

Referring to prior art Figures 5A and 5B, a configuration utilized to perform and package orthogonal polarization power-combining of two linearly polarized lasers 16,

18 having equal output powers (P) is shown. If required, the output of each of the lasers 16, 18 may undergo beam shaping, to obtain a beam shape of the desired dimensions. This is performed by appropriately designed optical modules 20 for each of the laser beams 16a, 18a. The output beams 20a, 20b from these modules 20 are provided as input to a polarization rotation power-combiner module 22. This module 22 rotates the polarization of one of the two beams 20a, 20b by 90 degrees and superimposes the two thus orthogonally polarized beams 20a, 20b upon one another. The two beams are emitted from individual lasers, consequently, their outputs 16a, 18a are independent of each other and have statistically independent phase and slightly different optical frequencies arising from the gain line width of the CO_2 molecule. The combined or superimposed beam 24 will have a cross polarized output. If each polarized laser beam has approximately equal output power, P, then the polarization combined beam has an output power of 2P.

The present state-of-the-art approach is to connect, in series, each of the lasers 16, 18 , with their respective beam shaping optical modules 20 and their polarization rotation power-combiner modules 22 end-to-end with the lasers 16, 18 as seen in Figures 5A and 5B. The end-to-end connection of the modules 20, 22 increases the length of the laser unit 16, 18, 20, 22 as seen in the present state-of-the-art of the cascading laser approach of Figure 1. The increase in length is undesirable because it increases the lasers sensitivity to vibration and leads to poorer pointing stability resulting from vibrations and thermal variation along the structure which can cause excessive twisting and bending of the optical board 26 upon which the optical components 16, 18, 20, 22 are located and attached. To minimize such problems, the common solution is to make the optical bench 26 upon which the lasers 16, 18 and modules 20, 22 are placed, rigid. This solution adds size, weight and cost. The elongated structure that results from this commonly utilized configuration makes the package unattractive for many applications that require the laser to be placed on moving platforms or in high noise industrial environments, (both of which are high shock and vibration environments in which long laser structures do not function well) and where a small "floor foot-print" is desired. Many of the disadvantages of this state-of-the-art orthogonal polarization power-combining packaging approach are similar to those cited above with respect to the end-to-end cascading of Figure 1.

SUMMARY OF THE INVENTION

The above discussed and other drawbacks and deficiencies of the prior art are overcome or alleviated by a laser of the present invention. In accordance with the present invention, the laser comprises a hermetically sealed housing and a plurality of waveguides positioned within the housing, the waveguides defining a plurality of channels for guiding a laser beam. Electrodes are positioned along the plurality of waveguides. A first electrode is connected to power supply and to distributed spiral inductors which are connected to the electrically grounded housing. A second electrode is connected to the housing. The laser is air or liquid cooled. A laser system comprises a housing, a plurality of waveguide lasers and a beam combiner for superimposing the output of the plurality of waveguide lasers, the beam combiner disposed on the housing. A laser system comprises a plurality of waveguide lasers and a beam combiner including a wavelength selective mirror for superimposing the output of the plurality of waveguide lasers.

BRIEF DESCRIPTION OF THE DRAWINGS

Referring now to the drawings wherein like elements are numbered alike in the several Figures,

Figure 1 illustrates a commonly used in-line cascaded laser configuration in accordance with the prior art;

Figure 2A depicts a two-mirror optical polarization rotator in accordance with the prior art;

Figure 2B depicts a three-mirror optical polarization rotator in accordance with the prior art;

Figure 3A depicts a three-mirror optical polarization rotator without beam deviation in accordance with the prior art;

Figure 3B depicts a schematic side view diagram of the angular relations of the polarization rotator of Figure 3A in accordance with the prior art;

Figure 4A depicts a four-mirror optical polarization rotator without beam deviation in accordance with the prior art;

Figure 4B depicts a schematic diagram of the angular relations of the polarization rotator of Figure 4A with two of its mirrors coated by a thin film quarter wave coating in accordance with the prior art;

Figure 5A is a top view of the present state-of-the-art package conceptualizing the juxtaposition of two linearly polarized lasers for polarization rotation power-combining in accordance with the prior art;

Figure 5B is a side view of the juxtaposition of two linearly polarized lasers for polarization rotation power-combining of Figure 5A in accordance with the prior art;

Figure 6A illustrates a cascaded laser configuration in accordance with the present invention;

Figure 6B illustrates the general type vertical bending experienced by a rectangular "bar" like cascaded laser structure held fixed at the center of the structure accordance with the present invention;

Figure 6C illustrates the general type lateral bending experienced by a rectangular "bar" like cascaded laser structure held fixed at the center accordance with the present invention;

Figure 6D illustrates an in-line cascaded laser configuration in accordance with the present invention;

Figure 7A illustrates a finite element model analysis of the vertical bending suffered by a cascaded laser of Figure 6A accordance with the present invention;

Figure 7B illustrates a finite element model analysis of this lateral bending suffered by a cascaded laser of Figure 6A accordance with the present invention;

Figure 7C illustrates a finite element model analysis of the torsional bending suffered by a cascaded laser of Figure 6A accordance with the present invention;

Figure 8 is a three dimensional view of the cascaded laser of Figure 6A accordance with the present invention;

Figure 9 illustrates a cross sectional view of a folded ceramic waveguide laser accordance with the present invention;

Figure 10 illustrates the juxtaposition of two folded ceramic waveguide lasers of Figure 9 in a cascaded configuration accordance with the present invention;

Figure 11A illustrates a top view of a diffusion cooled waveguide laser having an "NV" shaped waveguide structure in accordance with the present invention;

Figure 11B is an end view of the diffusion cooled waveguide laser of Figure 11A accordance with the present invention;

Figure 12A is an unfolded top view of a cascaded diffusion cooled waveguide laser utilizing two lasers illustrated in Figure 11A in accordance with the present invention;

Figure 12B is a first end view of the cascaded diffusion cooled waveguide laser of Figure 12A accordance with the present invention;

Figure 12C is a second end view of the cascaded diffusion cooled waveguide laser of Figure 12A accordance with the present invention;

Figure 13 is a cross sectional view of a cascaded diffusion cooled waveguide laser where the ends of each waveguide structure is a mirror image of the other in, accordance with the present invention;

Figure 14A is a top view of an "NV" folded ceramic waveguide laser structure in accordance with the present invention;

Figure 14B illustrates an unfolded top view of two ceramic waveguide lasers of Figure 14A positioned in a cascaded configuration with the ends of each waveguide structure being a mirror image of the other as in Figure 13 in accordance with the present invention;

Figure 15 is a cross sectional view of a cascaded diffusion cooled waveguide laser with its ceramic waveguide structure in close terminal contact with the grounded metal laser housing in accordance with the present invention;

Figure 16A is a cross sectional view of a diffusion cooled waveguide laser as per the top laser of Figure 15 showing superior heat conduction path for this configuration accordance with the present invention;

Figure 16B is a cross sectional view of a diffusion cooled waveguide laser as per the top laser of Figure 13 showing the inferior heat conduction for this configuration accordance with the present invention;

Figure 17 is a cross sectional view of a cascaded laser showing a laser beam turning mechanism housing which is hermetically sealed to the laser housing and used for directing a laser beam from one waveguide structure into the other waveguide structure accordance with the present invention;

Figure 18A is a side view of a cascaded laser showing the end mirror assembly with a laser beam turning mechanism accordance with the present invention;

Figure 18B is an end view of a cascaded laser showing the end mirror assembly with a laser beam turning mechanism accordance with the present invention;

Figure 19A illustrates a first exploded view of the end mirror assembly of Figures 18A and 18B accordance with the present invention;

Figure 19B illustrates a second exploded view of the end mirror assembly of Figures 18A and 18B accordance with the present invention;

Figure 20A illustrates an unfolded top view of the juxtaposition of four waveguide lasers in cascaded configurations for obtaining four times the output power of one laser in accordance with the present invention;

Figure 20B illustrates a first end view of the plurality of waveguide lasers in cascaded configurations of Figure 20A accordance with the present invention;

Figure 20C illustrates a second end view of the plurality of waveguide lasers in cascaded configurations of Figure 20A accordance with the present invention;

Figure 21A is a top view of the laser polarization rotation power-combiner of the present invention accordance with the present invention;

Figure 21B is a side view of the polarization rotation power-combiner of Figure 21A accordance with the present invention;

Figure 22 is a three dimensional view of the laser polarization rotation power-combiner of Figures 21A and 21B accordance with the present invention;

Figure 23A is a top view of the three dimensional view of the polarization rotation power-combiner of Figure 22 accordance with the present invention;

Figure 23B is a three dimensional view of the polarization rotation power-combiner of Figures 21A and 21B with a protective cover accordance with the present invention;

Figure 24A depicts an assembled view of a thin film polarizer accordance with the present invention accordance with the present invention;

Figure 24B depicts an exploded view of the thin film polarizer of Figure 24A accordance with the present invention;

Figure 25A is an exploded three dimensional view of a four-mirror polarization rotator accordance with the present invention;

Figure 25B is a plan view of the assembled polarization rotator of Figure 25A accordance with the present invention;

Figure 25C is a cross sectional view of a three-mirror polarization rotator accordance with the present invention;

Figure 26 is a three dimensional view of the polarization rotation power-combiner utilizing a combined three mirror polarization rotator and laser beam turning mechanism accordance with the present invention;

Figure 27 schematically depicts the laser beam paths and polarizations of the polarization rotation power-combiner of Figure 26 accordance with the present invention;

Figure 28A is a side view of the polarization rotation power-combiner of Figure 26 accordance with the present invention;

Figure 28B is a plan view of the polarization rotation power-combiner of Figure 26 accordance with the present invention;

Figure 28C is a first end view of the polarization rotation power-combiner of Figure 26 accordance with the present invention;

Figure 28D is a second end view of the polarization rotation power-combiner of Figure 26 accordance with the present invention;

Figure 29 depicts a folded "NV" waveguide in accordance with the prior art;

Figure 30 is a schematic representation of an optical frequency (or wavelength) power-combing approach utilizing the teaching of this invention;

Figure 31A shows data of the various rotational and vibrational oscillating lines of a CO_2 laser showing their relative power output; and

Figure 31B is a table of the oscillating lines of Figure 33A.

DETAILED DESCRIPTION OF THE INVENTION

Referring now to Figure 6A a cascaded laser configuration in accordance with the present invention is shown generally at 100. Two waveguide lasers 102, 104 are placed parallel to one another, i.e., by placing one on top of the other with a heat exchanger 106 such as a cooling plate 106 disposed therebetween. Two totaling reflecting mirrors 110, 112 in a laser beam turning mechanism 108 are utilized to redirect the free space propagating laser beam 114 180 degrees in order to direct the

laser beam 114 into and out of the two waveguide lasers 102, 104 thus providing a single waveguide laser cavity or resonator 100. It has been discovered that a free space propagation distance of about nine inches or less for the laser beam 114 emitted from a waveguide before it is re-coupled directly into another waveguide experiences sufficiently low losses for waveguide lasers having an active gain length of about 400cm or more. This discovery has made the cascaded approach of Figure 6A in which waveguides are parallel to one another a practical way of obtaining a higher power waveguide laser. The approach of Figure 6A provides a shorter and stiffer package (than that of prior art Figure 1) while suffering only an increase in height, and provides the advantage of a symmetric thermal design. The shorter package and symmetric thermal design of the proposed approach of Figure 6A over the prior art (Figure 1) yields superior stability in laser frequency output and beam pointing. Because of the narrow gain line at the gas pressure at which most diffusion cooled CO_2 lasers operate (approximately 100 torr), the increased frequency stability yields improved output power variation as the temperature varies.

Referring to Figure 6D, a cascaded laser configuration, in accordance with the present invention, is shown generally at 100a. Two waveguide lasers 102a, 104a are placed in line with one another on a heat exchanger 106a or a cooling plate 106a and a free space propagating laser beam 114a is directed between the waveguide lasers, thus providing a single waveguide laser cavity or resonator 100a.

Sufficiently small losses can be obtained when the laser beam 114a makes the transition from one waveguide laser to another waveguide laser through free space. It has been found that low losses can be obtained during such a transition for a free space path 114b up to approximately nine inches or less. This newly discovered fact makes the cascading of waveguide lasers as in Figures 6A and 6D possible.

In the cases of vertical bending where the laser is clamped in the center as schematically illustrated in Figure 6B and lateral bending as schematically illustrated in Figure 6C, the displacements ΔZ and ΔX, respectively, of the ends of the laser are much smaller for the configuration seen in Figure 6A than for that of the prior art (Figure 1). This leads to higher bending and twisting resonant frequencies in the configuration seen in Figure 6A than that of the prior art (Figure 1). Higher structural vibrational resonant frequencies are preferred over lower resonant frequencies because

higher vibrational resonance's are more difficult to be induced in the bar shaped laser head by environmental background noises or by the quick start up or stopping of a movable platform upon which the laser could be mounted. .

Another advantage of the configuration of Figure 6A is that of optical path length compensation under vibrating conditions. When the optical path length of the upper laser 102 is contracting due to a $+\Delta Z$ upward deflection of the ends of the laser head, the optical path length of the lower laser 104 is being stretched by the same amount. This in effect maintains, to first order, a constant optical length which maintains a constant laser output frequency. The laser heads 102, 104 utilize ceramic folded waveguides such as those seen in Figure 29, consequently when the laser head structure is vibrating with a lateral displacement $+\Delta X$, analysis indicates, to first order, that, as the outer arms 20, 144 of the folded waveguides are stretching so that their optical path length is increasing, the inner arms of the folded waveguides are contracting at the same time which decreases their optical lengths by approximately the same amount. Analysis indicates that this optical length compensation is again true to first order. This type of optical path length compensation in a folded waveguide again tends to maintain the laser frequency constant also under lateral vibration of the structure. A stable frequency output results in a stable amplitude output. In addition to these performance advantages, the smaller "footprint" of the configuration of Figure 6A is more suitable for operation in an adverse industrial environment such as on a robotic arm or other movable platform than that of the prior art (Figure 1) because of its more compact and rigid design.

Referring to Figure 7A, finite element analysis 116 performed for the vertical bending condition is shown. A lowest order vibrational resonance of 1,774Hz was obtained by placing two laser heads 102, 104 on top of one another with a common cooling passages 106 disposed therebetween. Each of the laser heads had dimensions of approximately 24 in. long (L) by 4 in. wide (W) by 3 in. high (H). Finite element analysis 118 performed for the lateral bending condition is shown in Figure 7B. A lowest order lateral vibrating resonance of 1809Hz was obtained for the illustrated structure using two laser heads 102, 104. Torsional bending finite element analysis 120 using the same waveguide structure is shown in Figure 7C. The torsional bending resonant frequency was found to be 2172Hz. These high resonant frequencies are an

indication of the stiffer design for a given weight that the proposed new configuration provides over the prior art (Figure 1). Table I summarizes the analysis.

TABLE I

Type of Vibration	**Resonance in Hz**
Vertical	1,774
Lateral	1809
Torsional	2172

Table I: Finite Element Calculation Resonance's Results for the Cascaded NV Lasers of Figure 6A

Referring to Figure 8, an overview sketch of the cascaded laser configuration 100 utilizing two lasers 102, 104 in and the free space laser beam turning mechanism 108, is shown. Using these lasers 102, 104 in the indicated configuration, 240W of output power has been obtained which is essentially twice the power output of each of the lasers 102, 104 separately. This indicates that the losses associated with the free space propagation losses when the laser beam 224 propagates between two waveguides having a total gain length of approximately 400cm are not excessive while the beam is also being redirected 180 degrees and reentering the second waveguide. The configuration of Figure 8 maintains the free space propagation distance sufficiently short such that the losses are small enough so as not to be bothersome. This free space propagation distance used in obtaining the 240W output was about 4.2 inches. In another experiment, 165 Watts was obtained when a $^{13}C^{16}O_2$ isotope gas was used in both lasers 102 and 104. This isotope is known to have considerably lower power output than the commonly used $^{12}C^{16}O_2$ molecule (i.e., approximately 2/3 the output power of $^{12}C^{16}O_2$).

Referring to Figure 9, the use of an "N" shaped ceramic waveguide 308 and a heat exchanger using either liquid cooling 324 or air cooling 334 is shown as an example. Other more complicated waveguide folding patterns could be utilized in Figure 9 such as an "NV" pattern of prior art Figure 29. Referring to prior art Figure 29, therein depicted is a folded "NV" waveguide 16 such as described in Patent Application No. PCT/US98/05055 is shown. U. S. Patent No. 5,610,936 describes a more elaborate folding arrangement and describes a rectangular ceramic folded diffusion cooled CO_2 waveguide structure that contains two triangular end sections in

which a grid waveguide structure consisting of two sets of parallel waveguide channels intersecting at right angles and optically coupled by the strip mirrors placed along edges of the triangular end sections. This approach has yielded approximately 200W of output power. The folded waveguide 20 of prior art Figure 29 is folded in the shape of an "NV." It can yield 125W of output power in a laser head having dimensions of approximately 24 inches (L) x 4 inches (W) x 3 inches (H).

Returning to Figure 9, a laser head (or device) 300 has a one piece metal housing 302 which also acts as an electrical ground for the laser head. The metal housing 302 defines an interior volume 360. A metal electrode 304 and a non-oxygen depleting, non-particulate generating metal electrode 306 in electrical contact with the metal housing 302, having a ceramic waveguide 308 disposed therebetween, are positioned within housing 302. Waveguide 308 has waveguide channels 310 defined therein. An RF power supply 312 is connected to electrode 304 by a co-axial cable 314 through a vacuumed sealed (hermetically sealed) RF connector 316 and a phase matching co-axial line 318 through a vacuumed sealed (hermetically sealed) RF connector 320. A coolant sealing plate 322 defining an internal heat exchanger in the nature of cooling passage 324 is mounted to housing 302. A seal 302aa forms a seal between the housing 302 and the cooling passage 324. Alternatively the internal cooling passage 324 could be located in housing 302 and be sealed off by plate 322. Alternatively, cooling of the laser may be accomplished by a heat exchanger in the nature of an air-cooled or finned heat exchanger 334. Ceramic waveguide 308 overhangs, on all sides, electrodes 304 and 306, thereby preventing a discharge from forming between the edges of the top and bottom electrodes 304, 306. This overhang of waveguide 308 (or indentation of electrodes 304 and 306) assures that the electrical resistance between the electrodes 304, 306 along the surfaces of the ceramic is greater than through the waveguide at all points.

A distributed inductance assembly 326 is positioned above electrode 304 by a ceramic spacer 328. One end of the distributed inductance assembly 326 is electrically connected to electrode 304 by stiff electrical wires or posts 330 at one end, and at the other end by the metal low inductance C-spring 332 to the metal housing which serves as a electrical ground. The metal C-spring 332 serves two functions. First the metal C-spring 332 provides an electrical conduction path to ground and secondly the C-spring

holds the internal pieces together by compression. Laser 300 employs a clamping scheme in which the external clamping plate used in the prior art being part of a flexible laser housing, is eliminated. It is replaced by an arrangement consisting of a continuous C-spring 332 (made from a resilient material such as gold plated Beryllium Copper) in combination with ceramic spacer 328. The C-spring 332 provides both a well defined clamping force and a low inductance connection of the inductor assembly 326 to the metal housing 302. These two features of the C-spring 332 in this invention differentiate the C-spring of this invention over the prior art where the C-spring is used only to define a well defined clamping force. This arrangement provides a clamping force which is very uniform and has a magnitude which does not result in fracture of the ceramic components. Furthermore, this clamping arrangement does not require the thinning of the housing 302 thereby improving the stiffness and resulting alignment stability relative to conventional designs. In addition, ceramic spacer 328 is a simple, two piece component and has a lower cost than the ceramic component used in the prior art devices. Air cooling can be accomplished through metal fins 334 depending upon housing 302 (for low power lasers), fins 334 are preferably located at the bottom of the housing as shown, or by flowing a liquid or forced air through cooling passages 324 may be used for higher power lasers (100W and greater), or by both as shown in Figure 9.

Referring to Figure 10, the positioning of the two laser housings 302a, 302b of Figure 9 in the cascaded configuration of Figures 6A or 8 with the exception that an "NV" ceramic waveguide structure 308 of prior art Figure 29 is shown as an example instead of an "N" waveguide structure of Figure 9. In the configuration of Figure 10, all of the parts comprising the top laser head 302a and the bottom laser head 302b are identical. However, the electrode 306 and the ceramic waveguide 308 are positioned differently in the bottom laser 302b than in the top laser 302a, i.e., the ceramic waveguide 308b of the laser 302b is positioned directly against the raised portion 352b of the bottom laser housing 302b, while the in laser 302a, the electrode 306 is positioned directly against the raised portion 352a of the top laser housing 302a. This positioning change allows the identical ceramic waveguide structure 308 to be used in both the upper 302a and lower 302b lasers. This offers a commonality of parts cost advantage. An RF power supply 312 is connected to electrode 304 by way of the metal

post 330 supporting the distributed spiral inductors 326. The 240 Watt and the 165 Watt results mentioned previously were obtained with the configuration of Figure 10.

The approach of Figure 10 suffers from the fact that the laser beam (not shown) exiting the waveguide arm of one of the lasers does not experience a mirror image of the waveguide channel it left when it enters the other waveguide channel. For example, the portion of the laser beam (not shown) adjacent to electrode 306 exiting the waveguide structure 308a (or channel 310a) of the top laser head 302a enters the waveguide structure 308b (or channel 310b) of the bottom laser head 302b on the opposite side of the waveguide 308a away from its electrode 306. This non-mirror image is not ideal and causes slightly higher losses, and thus a slightly lower output power than if a waveguide mirror image arrangement is maintained. Consequently, even higher output powers than the 240 Watts could have been obtained in the experiment referred to earlier. The mirror image arrangement will be discussed later.

Referring to Figure 11A, a diffusion cooled waveguide laser 400 is shown having a folded "NV" shaped waveguide 408 configuration including five channels in a zigzag pattern, with five totally reflecting mirrors 402 and the one semi-reflecting output mirror 410 which provides the output beam 224 to the two 45 degree angled totally reflecting mirrors 404, 406 as part of a laser beam turning mechanism 414 positioned exterior to the waveguide laser 400. The laser beam turning mechanism 414 directs the laser beam 224 into the beam shaping optical arrangement 220 as described in Patent Application No. PCT/US98/05055, which is incorporated herein by reference. Figure 11B illustrates the external front-end view of the laser 400 of Figure 11A for completeness.

Referring to Figure 12A an unfolded top-down view of an "NV" waveguide of a cascaded diffusion cooled waveguide laser 102, 104 based upon the arrangement of Figure 10 is shown. Figure 12A shows the individual five-channel folded waveguide lasers 102, 104 have totally reflecting mirrors 402, the output mirror 410 and the two openings 420 where the laser beam 114 exits and enters the lasers 102, 104. The two mirrors 110, 112 directing the free space laser beam 114 between the lasers 102, 104 are also shown. The laser beam turning mechanism 108 is hermetically sealed to the laser housings 102, 104. Two 45 degree angled output mirrors 404, 406 directing the output beam 224 to a beam shaping optical arrangement 220 are also shown

schematically. Figure 12B illustrates a front end view of the configuration which shows the laser beam turning mechanism 108. Figure 12C illustrates a back end view of the configuration, which shows the laser beam turning mechanism 414. From Figure 11A and 12A it will be appreciated that this arrangement can accommodate lasers having a larger number of folded waveguide channels than shown in Figure 12A.

Referring to Figure 13, a cross sectional view of the internal structure of a cascaded laser, again using two lasers 302a, 302b that utilize ceramic "NV" folded waveguides 308a, 308b is shown. The internal arrangement shown is the preferred embodiment for the lowest loss transition where the laser beam (not shown)exiting and entering from and into the top 302a and bottom 302b laser heads experiences a mirror image in the propagation process. For the case shown, the gas discharge within the ceramic waveguide 308a, 308b is in contact with a titanium electrode 306 through the channel 310a, 310b of the slotted waveguide. The electrode 306 is in turn in contact with the aluminum housing 302a, 302b at 352a and 352b. This arrangement has the benefit of providing a mirror image for the beam propagating between the top 302a and bottom 302b lasers. However, it has the disadvantage over the arrangement of Figure 10 in that it requires two different ceramic waveguide structures 308a, 308b, thus increasing the number of different parts to be maintained in inventory.

Referring Figure 14A, a top down internal view of a folded "NV" ceramic waveguide structure 408 is shown, which differs slightly from that of Figure 11A (namely, the folding pattern is inverted). It has been found that either configuration can be used. Figure 14B shows the use of two lasers 400 of Figure 14A to assemble a cascaded laser with the laser beam 420 transitioning from one waveguide 408a, bending 180 degrees and reentering a second waveguide 408b and experiencing a mirror image of the waveguide 408a from which it was emitted. While this mirror image technique of Figure 14B offers the advantage of lower internal losses, it has the disadvantage as having different upper and lower ceramic waveguide structures 408a, 408b which adds to inventory as discussed in regard to Figure 10 of other section. The two different patterns of the waveguide structures is depicted by 408a and 408b of Figure 14B.

Titanium has a poor thermal conductivity when compared to aluminum and ceramic materials. In the upper laser 302a of Figure 10 and in both the upper 302a and

lower 302b lasers of Figure 13, the titanium electrode 306 is in contact with the discharge 310a, 310b on one side of the electrode 306 and with the aluminum housing 302a, 302b on the other side of the electrode 306. A heat exchanger in the nature of cooling passages 324 is provided between the laser housings 302a, 302b. Most of the heat has to flow from the discharge 310, through the titanium electrode 306 through the interface between the titanium electrode 306 and the aluminum housing 302a, 302b and finally into the aluminum housing 302a, 302b. This is not an optimum thermal design arrangement.

A preferred technique for conducting away the heat is shown in Figure 15. In Figure 15, that surface of the ceramic waveguides 308a, 308b which does not contain the waveguide channels 310a, 310b is placed directly against that uplifted portion 352a, 352b of the aluminum housing 302a, 302b adjacent where the cooling passages 324 are provided. In this arrangement most of the heat is conducted from the discharge 310a, 310b within the folded waveguides 308a, 308b into the ceramic structure 308a, 308b, through the ceramic structure and into the cooled aluminum housing 302a, 302b(Figure 16A). The titanium electrode 306 covering the opposite side of the ceramic waveguide structure 308a, 308b has an aluminum electrode 304a placed over the titanium electrode 306 (forming a single hot electrode) for good electrical contact to the distributed spiral inductors 326 used to tune out the capacitance of the electrodes of the ceramic waveguide assembly. The aluminum electrode 304a and the titanium electrode 306 form a single highly electrically conductive electrode. Titanium possesses a native oxide (TiO_2) that has a low thermal coefficient of expansion that is close to the host (Ti) metal thereby generating little or no particulate matter under alternate heating and cooling of the electrode. The reason for the use of a titanium electrode 306 in contact with the discharge 310 is described in Patent Application No. PCT/US98/05055, RF Excited Waveguide Laser, by R.A. Hart, J.T. Kennedy, E.H. Mueller and & L.A. Newman; filed on March 13, 1998 based on U. S. provisional patent application No. 60/041,092 filed on March 14, 1997, which is incorporated herein by reference. Figure 16B illustrates the positioning of the ceramic waveguide structure 308a, 308b, with the titanium electrode 306 in contact with the discharge 310 with the waveguides 308a, 308b on one side and the cooled aluminum housing on the other, as described in Patent Application No. PCT/US98/05055. It is clear that heat conduction from the discharge

into the poor heat conducting titanium electrode 306 and then into the superior heat conducting aluminum housing 302a, 302b as illustrated in Figures 9, 10 and 13, is not as good as in Figure 15. To more clearly show the advantages of the arrangement of Figure 15, Figures 16A and 16B are provided. Undesirable heating of the CO_2:N_2:He gas ballast is higher in the approach of Figure 16B over the preferred arrangement of Figure 16A because of the superior heat flow from the ceramic into the aluminum in contact with it and into the coolant. The discharge and the gas ballast chamber are kept cooled. Heat from the ceramic 308a, 308b and the aluminum electrode 306 will flow into the gas ballast as well as from the ceramic spacers 328 and the spiral inductors 326. From a laser efficiency standpoint it is desirable to minimize the heating of the CO_2 laser gas mixture in the gas ballast area of the laser housing 302a, 302b. The approach of Figure 16A accomplished this because of the poor heat conduction path through the titanium part 306 into the aluminum part 304 of the hot electrode in contact with it, into the posts 330 holding up the distributed spiral inductors 326 and finally into the gas within the gas ballast area of the laser housing 302.

Referring to Figure 17, a cross sectional view of the cascaded lasers 102, 104 is shown including two angled mirrors 110, 112 in the laser beam turning mechanism108 for directing the laser beam 114 from the waveguide 308a of one laser 102 into the waveguide 308b of the other laser 104 while experiencing a mirror image of the waveguide aperture that the laser beam 114 left. An intermediate plate 500 is used as shown along with O-ring seals 504 to hermetically seal the apertures 502 of the upper 102 and lower 104 laser head and to hermetically seal the laser beam turning mechanism 108 to the intermediate plate 500. A cooling passage 510 between the upper 102 and lower 104 laser is shown. The O-ring seal 506 prevents coolant leakage. In Figure 17, the ceramic waveguide structure 308a, 308b and the titanium electrodes 306 are placed as illustrated in Figure 16A which is the preferred embodiment for the best thermal cooling of the discharge. Figure 18A shows a side view and Figure 18B an end view of the cascaded laser assembly 102, 104 showing a mirror housing 256 with the laser beam turning mechanism 108. Figures 19A and 19B illustrate exploded views of the end mirror assembly showing the intermediate plate 500 and its O-ring seals 504 and laser beam turning mechanism 108.

Figure 20A illustrates a cascaded configuration that has been expanded to include four lasers 102, 104, each having multiply folded waveguides 408 cascaded together in one feedback cavity to obtain essentially four times the output power of one laser. Accommodating four lasers as shown in Figure 20A requires two vertical laser beam turning mechanisms 108, and one horizontal laser beam turning mechanism 108a to redirect the laser beam 114 into and out of the waveguides 408 of any two lasers and one laser beam turning mechanism 414 to direct the output beam 224 into the beam correcting optics 220. Essentially, two of the assemblies of Figures 10, 13 or 15 are used side by side with the laser beam turning mechanism 108 mentioned above. For the reasons given above, two assemblies of Figure 15 positioned side-by-side are the preferred approach. Figures 20B and 20C are end views of the laser arrangement of Figure 20A.

Combining the output of sealed-off, waveguide CO_2 lasers that utilize multiple folded waveguide structures by an orthogonal polarization power-combining scheme is particularly appealing because such waveguide laser configurations already have a polarized output if they have a metal electrode in contact with the discharge in the waveguide; which is the preferred arrangement. Waveguide lasers have their optical electronic field polarized parallel to the plane of the metal electrodes within the laser housing. One method of obtaining higher power in waveguide lasers, is to increase the number of folds (channels) in a waveguide structure thereby increasing the length of the gain region. Unfortunately, there is a practical limit on the number of waveguide folds that can be cost effectively accommodated from an ease of resonator alignment standpoint in a folded waveguide laser. For example, mirrors need to be individually aligned during the manufacturing process for optimum power output. The larger number of waveguide channels, the larger the number of mirrors that need to be aligned to ensure optimum laser performance. The major advantage of utilizing polarization power-combining techniques with two sealed-off CO_2 lasers that encompass multiple waveguide folding techniques is the alignment of one half of the mirrors of a single resonator on each of two individual lasers, while the cascading approach of Figure 1 requires the alignment of twice the number of mirrors on a single laser resonator which is a more difficult and time consuming task. Either approach should yield higher output power and move the output power of diffusion cooled waveguide CO_2 lasers

into the output power performance region of diffusion cooled CO_2 slab lasers and into the lower power region addressed by flowing gas lasers.

The use of reflecting mirrors to provide the polarization rotation required in a power-combining design to obtain higher output power levels is very attractive. Reflecting mirror polarization rotation power-combining techniques can utilize similar mirrors used within the laser head. This is attractive because such mirrors are known to be able to handle the power without optical damage while causing minimum or no optical beam distortion when compared to the use of other polarization rotating techniques such as half wave plates. Half wave plates suffer from non-uniform birefringence caused by heat generated by the small absorption in the matter of the high power laser beam as it propagates through the device.

Referring to Figures 21A and 21B, an example of a polarization rotation power-combining configuration of this invention is shown. The advantages of this polarization rotation power-combining configuration results from achieving a shorter, more rigid and compact configuration than the approach depicted by Figures 5A and 5B. This in turn results in superior laser pointing, and power output stability. The preferred approach of this invention utilizes the top surfaces of two laser housings 216, 218 of Figure 9 or Figure 16A as optical benches upon which to attach the beam shaping modules 220a, 220b and the polarization rotation power-combining module 222.

Continuing in Figures 21A and 21B, the output laser beams 214 are brought up onto the top surface of each of the two laser housings 216, 218 by laser beam turning mechanism 208. Such laser beam turning mechanism 208 is disclosed in Patent Application No. PCT/US98/05055. The output laser beams 214 are converted from elliptically shaped beams to round beams of the desired diameter by the beam shaping modules 220a, 220b such as disclosed in Patent Application No. PCT/US98/05055. The beam shaping modules are positioned on top of the laser housings 216, 218. Elliptically shaped output beams occur from waveguide lasers when the waveguide of the laser is of rectangular shape. The two round linearly polarized beams (not shown in Figures 21A and 21B) formed by the beam shaping modules 220a, 220b are each then passed through the polarization rotation power-combiner module 222 to produce a cross polarized output beam 226. The polarization rotation power-combiner module

222 is also positioned and fastened on top of the two laser housings 216, 218 as shown. This preferred configuration results in a slightly higher structure but a considerably shorter, stiffer and more rigid structure which has superior performance in adverse environments.

Referring to Figure 22, the polarization rotation power-combining module 222 is shown comprising a polarization rotator 228, a plurality of mirrors 230, and a polarizer 232. Sealed-off waveguide lasers 216, 218 having, for example, five folded waveguide channels (not shown) in a saw-tooth pattern and six laser feedback mirrors (not shown) in mirror housings 256 as described in Patent Application No. PCT/US98/05055 are shown as an example. These components of the polarization rotation power-combiner are mounted on a common plate 234 which in turn is mounted on the top surface of the two laser housings 216, 218 with their cooling plates 262 as shown. While a four-mirror polarization rotator 228 is shown, it will be appreciated that three-mirror polarization rotator 228 can also be used. Each of the two lasers 216, 218 is individually attached on a mounting plate 260 at three contact points 258 as shown in Figure 22. The other polarization rotation power-combining components are beam redirecting mirrors 230 and thin film polarizer 232.

Referring Figure 23A, a top-down view of the polarization rotator power-combining module 222 is shown including the laser beam paths 224a, 224b, 226 through the various optical elements of the power-combining module 222. The laser beam 224a from the upper laser 216 of Figure 23A exits the upper beam shaping module 220a horizontally polarized (i.e., parallel to the plane of the paper) as indicated by the " $\underline{\updownarrow}$ " arrow. This beam 224a is redirected as shown by mirrors M_1 and M_2 and made to propagate directly through the thin film polarizer 232 arranged at Brewster's angle, θ_B, as is well known in the art. For CO_2 laser wavelengths, ZnSe thin film polarizers (TFP) are commonly used for this purpose. The laser beam 224b from the second laser 218 exiting the lower beam shaping module 220b also has a horizontal polarization in the plane of the paper (not shown). Each of the waveguide lasers 216, 218 naturally has a horizontal polarization in the plane of the paper because of the relationship between the laser beam and the metal electrode in contact with the laser beam. The polarization for the waveguide lasers 216, 218 results from the use of the metal electrodes (not shown) in contact with the plasma discharge region within the

ceramic waveguides (not shown) as described in Patent Application No. PCT/US98/05055. Such polarization also occurs from the cascaded lasers 102, 104 of Figure 8. Consequently, either of these lasers can also be substituted for the two lasers 216, 218 depicted in Figure 22 and Figures 23A and 23B. This polarization power-combining configuration can be used with any two linearly polarized lasers. Horizontal polarization is discussed as an example but vertically polarized lasers can also be utilized by this approach with a slight modification of the components and their positioning.

The horizontally polarized beam 224b from the lower beam shaping module 220b of Figure 23A propagates through the four-mirror polarization rotator 228 which rotates the polarization of the laser beam 224b by 90 degrees (i.e., perpendicular to the plane of the paper) as shown in Figure 23A by the "●" dot. A three-mirror polarization rotator can also be used and is preferred (Figure 25C shows a three-mirror polarization rotator 228). The now vertically polarized beam 224b (electric field now perpendicular to the plane of the paper) is redirected by mirrors M_3 and M_4 to the front of the thin film polarizer (TFP) 232 at the same location where the horizontally polarized beam 224a exits the TFP 232 as is well known in the art. Because of its vertical polarization, this beam 224b is reflected off the front surface of the TFP 232, which is disposed at Brewster's angle, θ_B. The horizontal polarization of beam 224a allows this beam to be transmitted through the thin film polarizer 232. Proper super positioning alignment of the two orthogonal polarized beams 224a, 224b obtains one output laser beam 226. Combining the two orthogonal polarized beams 224a, 224b, which are statistically independent in phase and frequency, because each is emitted from a different laser, results in one output beam 226 with cross polarization. If the powers of each of the beams 224a, 224b leaving the TFP 232 are equal to P, then each of the cross polarized components thereof will have the same power and the total power of the single output beam 226 will be 2P. Either manual or automatic electronic control of the output power adjustments of each laser 216, 218 can be utilized to insure that the powers of each beam 224a, 224b leaving the TFP 232 are equal. Circularly polarized output beams can be obtained instead of randomly polarized beams by frequency and phase locking the two lasers 216, 218 together by techniques well known in the art. While this approach may be suited for special applications where cross polarization can not be

tolerated, the added cost and complexity of providing frequency and phase locking of two lasers makes this approach not attractive for most commercial or industrial applications. As shown in Figure 23B, a cover 236 can be placed over the entire polarization rotation power-combining module 222 of Figures 22 and Figures 23A to keep out dust, water, etc.

Propagating several hundred Watts of power through the thin film polarizer 232 without generating excessive heating effects, which can distort the beams 224a, 224b, requires good heat conducting design for the thin film polarizer housing 232a. Maintaining good flatness so as not to optically distort the thin film polarizer 232 as well as for good heat conduction is important for obtaining good final laser beam quality. Figures 24A and 24B illustrate a thin film polarizer 232 including a housing 232a. A thin film coated ZnSe crystal 240 is pressed against a thick flat block 232b by a recessed collar 242 that has springs 242a for pressing against the ZnSe crystal 240. The collar 242 is secured against the block 232b by screws 244. The block 232b is secured to the common plate 234 of the polarization rotation power-combining module 222 of Figure 22. The surface of the block 232b, which can be fabricated from copper, in contact with the ZnSe crystal is polished or diamond turned machined flat for good heat conductivity and for maintaining a distortion free thin film coated ZnSe polarizer 240.

Figures 25A and 25B illustrate a four-mirror polarization rotator 228 depicted in Figures 4A and 4B, that is part of the polarization rotation power-combining module 222. In the four-mirror polarization rotator 228 two of the four mirrors require a quarter wave ($\lambda/4$) coating to achieve the 90 degree polarization rotation. The three-mirror configuration does not require such coating and is therefore preferred. A four-mirror polarization rotator is more sensitive to temperature and wavelength variations and is more costly than the three-mirror rotator because of the extra mirror and the need for quarter wave ($\lambda/4$) thin film coatings on two of the mirrors. The mirrors 246 are held up against the rotator housing 228 by a wave washer 248, metal disk 250 and snap ring 252 arrangement as shown. The three-mirror polarization rotator of Figures 3A and 3B can be utilized instead of the four-mirror design if one does not object to a slightly higher vertical dimension for the rotator. A three-mirror polarization rotator 228 is depicted in Figure 25C showing an undeviated optical path 224b.

A three-mirror polarization rotator 228 can also be used with a beam displacement as depicted by Figure 26 by replacing one of the laser beam turning mechanisms 208 of Figure 22 with a version of the polarization rotation of Figure 2B to obtain a laser power-combiner. Figure 26 illustrates a version of this approach.

Referring to Figure 26, one of the horizontally polarized lasers 216 remains the same as in Figure 22. It maintains the same laser beam turning mechanism 208 and beam forming optics modules 220b for laser 216 as in Figure 22. However, the other laser 218 has a three-mirror arrangement 208a that serves simultaneously as a three-mirror polarization rotator and a laser beam turning mechanisms 208. The added optical distance the laser beam travels (not shown) in the horizontal direction within this combined polarization rotator and laser beam turning mechanism 208a means that the beam shaping module 220a is shorter for this laser than for the laser shown in Figures 22 and Figures 23A and 23B.

Referring to Figure 27, the three-mirror arrangement 208a for the laser configuration of Figure 26 is shown schematically. The laser beam turning mechanism 208, and the optics, for the first laser 216 remains the same as in Figure 22. Assume that this laser 216 has a power P_1 and is horizontally polarized. The mirrors 274, 276, 278 of the three-mirror arrangement 208a for the second laser 218 are configured such that the output beam of laser 218 is in the form of an inverted L (i.e.,"Γ") as shown in Figure 27. In addition to vertically redirecting the beam 224a and displacing it horizontally, the three-mirror arrangement 208a also rotates the polarization of the laser beam 224a by 90 degrees (i.e., from horizontal to vertical polarization) in the manner depicted in Figure 2B. Assume that this laser 218 has a power of P_2. The two orthogonally polarized beams 224a, 224b are now directed into the thin film polarizer 232 so as to have the two output beams 224a, 224b superimposed upon one another as described above. This power combining process of two orthogonally polarized beams yields a round laser beam that has cross polarization whose power output $P_o = P_1 + P_2$. If P_1 and P_2 are equal to P then the power out of the power-combining module, P_o equals 2P.

Referring Figures 28A, 28B, 28C and 28D, end, side and top down views of the power-combining assembly of Figures 26 and 27 are shown. Figure 28B illustrates the beam path within the power-combining module 222.

The power combining configurations of Figures 26, 27 and 28A – 28D have an advantage over the power combining packaging of Figures 22 and 23A and 23B because fewer mirrors are utilized. For example, the four-mirror and the three-mirror polarization rotation power-combining arrangement of Figures 22 and 23A and 23B utilized eight and seven mirrors respectively in addition to the four mirrors required in the two laser beam turning mechanisms 208. The power combining packaging of Figures 26, 27 and 28A – 28D utilize four mirrors in addition to the four mirrors in the two laser beam turning mechanisms 208, 208a. This amounts to four fewer mirrors when compared with the power-combiner utilizing the four-mirror rotator 228 and three fewer mirrors when compared with the power-combiner utilizing the three-mirror rotator 228.

The power-combining configuration of Figures 26, 27 and 28A – 28D has a disadvantage over the power-combining configuration of Figures 22 and 23A and 23B because of the larger number of non-common parts that are needed thus increasing inventory costs. For example, the beam shaping modules 220a, 220b for each of the two lasers 216, 218 are in different locations which prevents the use of off-the-shelf, high volume lasers without modifications for use in the laser power combining package. For these reasons, the use of a three-mirror rotator 228 in the packaging approach of Figures 22 and 23A and 23B is preferred for the polarization rotation power-combining configuration approach.

In many applications a cross-polarized output is not desired but a linear output polarization is required. Another power-combining approach is frequency (or wavelength) power-combining and it has a linear polarized output. Frequency power-combining can take advantage of the packaging scheme of Figure 21A and enjoys all of its advantages detailed earlier in accordance with this invention. The only change to the orthogonal polarization power-combining module 222 of Figures 21A and 21B and Figures 23A and 23B is that two mirrors M_a 280 and M_b 282 may be utilized for the frequency power combining module as illustrated in Figure 30. Note that the frequency power-combining module of Figure 32 is much simpler than the polarization power-combiners of Figures 22 and 23 or Figures 26 and 28. It has much fewer components, which yields considerable cost advantages. The disadvantages of frequency power-combining is that the output consists of two optical frequencies and that the optical

losses associated with frequency selective optical components are higher than for the polarization rotators. Present day optical frequency selective mirrors utilizing thin film coatings, as it is well known in the state-of-the-art, are considerably less expensive and have lower optical losses than optical gratings and are therefore preferred as the optical frequency selective components in Figure 30 if the frequency difference(i.e., wavelength difference) between the two lasers 216, 218 is sufficiently large.

CO_2 lasers can make optimum usage of frequency power-combining because CO_2 lasers can be made to oscillate on anyone of many different output wavelengths by utilizing a specific wavelength selective, partially reflecting output coupling mirror (not shown) on one of the lasers 216 or 218 and allowing the other laser to operate at the normal wavelength that CO_2 laser favor; namely, 10.6 μm.

Figure 31A and the table in Figure 31B illustrates the numerous vibrational and rotational lines at whose wavelength a CO_2 laser can oscillate. Note that some lines have greater output powers than other lines. Note also for example, that strong power output occurs on line 10P20 at approximately 10.6 μm and on lines 9R18 or 9R20 at approximately 9.3 μm for the CO_2 laser. There are other strong lines but these are chosen as an example. The frequency separation between these two lines is sufficiently great that wavelength reflective, selective thin-films, deposited directly on the laser output coupling mirrors, can be used to cost effectively perform the frequency selection to enable one laser of Figure 30 to oscillate at wavelength $\lambda_1 = 9.3$ μm (for example) while the other laser oscillates at $\lambda_2 = 10.6$ μm. Mirror M_a is highly reflective over a wide range of wavelengths and redirects the laser beam 224a of laser 220a of wavelength λ_1 onto mirror M_b 282 at the same location where laser beam 224a of wavelength λ_2 exits mirror M_b 282. Mirror M_b 282 has a thin-film coating that is highly reflective of wavelength λ_1 while being highly transparent to wavelength λ_2. Therefore, laser beam 224b is propagated through mirror M_b 282 while laser beam 224a is reflected by mirror M_b 282. If the power P_a of laser beam 224a is equal to power P_b of laser beam 224b, the output power is $P_a + P_b = 2P$ if the power of each of the two beams equal P. The power adjustment of the RF power supplies is used to make each beam equal in power. The output has the same linear polarization possessed by each of the two lasers. The output will consist of two wavelengths λ_1 and λ_2. For most material working applications, the two wavelengths will not have an adverse effect.

Some materials have different absorptions at the two wavelengths of the CO_2 laser (i.e., example 9.3 μm and 10.6 μm) emitted by the frequency power combined laser. Adjusting the output power from each of the RF power supplies driving each laser can provide the same amount of material heating or ablation effects on the material as the two different wavelengths. In this manner, compensation can be made for the different absorption at the two different wavelengths if required.

While preferred embodiments have been shown and described, various modifications and substitutions may be made thereto without departing from the spirit and scope of the invention. Accordingly, it is to be understood that the present invention has been described by way of illustration and not limitation.

CLAIMS

What is claimed is:

1. A laser comprising:

a housing; and

a plurality of waveguides positioned within the housing, the waveguides defining a plurality of channels for guiding a laser beam.

2. The laser as set forth in Claim 1 wherein the plurality of waveguides are positioned substantially co-planar with another.

3. The laser as set forth in Claim 1 wherein the plurality of waveguides are positioned substantially parallel with one another.

4. The laser as set forth in Claim 1 further comprising a laser beam turning mechanism for receiving a laser beam from a first channel and directing the laser beam into a second channel.

5. The laser as set forth in Claim 4 wherein the waveguides are positioned substantially parallel to one another.

6. The laser as set forth in Claim 5 further comprising a heat exchanger connected to the housing for conducting heat away from the laser.

7. The laser as set forth in Claim 6 wherein the heat exchanger is interposed between the plurality of waveguides.

8. The laser as set forth in Claim 5 further comprising:

a first electrode positioned along a first surface of the plurality of waveguides and connected to a power supply; and

a second electrode positioned along a second surface of the plurality of waveguides and connected to the housing.

9. The laser as set forth in Claim 8 wherein the first electrode comprises aluminum.

10. The laser as set forth in Claim 8 wherein the second electrode comprises a host metal having a native oxide having a thermal coefficient of expansion substantially equal to the host metal.

11. The laser as set forth in Claim 11 wherein the host metal comprises titanium.

12. The laser as set forth in Claim 5 further comprising:

an electrode having a first and second part positioned along a first surface of the plurality of waveguides and connected to a power supply wherein the second part of the electrode is positioned between the first part of the electrode and the plurality of waveguides and wherein the plurality of waveguides are connected to the housing.

13. The laser as set forth in Claim 12 wherein the first part of the electrode comprises aluminum.

14. The laser as set forth in Claim 12 wherein the second part of the electrode comprises a host metal having a native oxide having a low thermal coefficient of expansion that is close to the host metal.

15. The laser as set forth in Claim 14 wherein the host metal comprises titanium.

16. The laser as set forth in Claim 5 further comprising:

a first electrode positioned along a first surface of a first waveguide of the plurality of waveguides and connected to a power supply;

a second electrode positioned along a second surface of the first waveguide of the plurality of waveguides and connected to the housing;

a third electrode having a first and second part positioned along a first surface of a second waveguide of the plurality of waveguides and connected to a power supply wherein the second part of the electrode is positioned between the first part of the electrode and the second waveguide of the plurality of waveguides and wherein the second waveguide of the plurality of waveguides is connected to the housing.

17. The laser as set forth in Claim 16 wherein the first electrode comprises aluminum.

18. The laser as set forth in Claim 16 wherein the second electrode comprises a host metal having a native oxide having a thermal coefficient of expansion substantially equal to the host metal.

19. The laser as set forth in Claim 18 wherein the host metal comprises titanium.

20. The laser as set forth in Claim 16 wherein the first part of the electrode comprises aluminum.

21. The laser as set forth in Claim 20 wherein the second part of the electrode comprises a host metal having a native oxide having a thermal coefficient of expansion substantially equal to the host metal.

22. The laser as set forth in Claim 21 wherein the host metal comprises titanium.

23. The laser as set forth in Claim 4 wherein the laser beam turning mechanism comprises at least one mirror.

24. A laser system comprising:

a housing;

a plurality of waveguide lasers; and

a beam combiner for superimposing the output of the plurality of waveguide lasers, the beam combiner disposed on the housing.

25. The laser system as set forth in Claim 24 further comprising a plurality of laser beam turning mechanisms for directing the output of the plurality of waveguide lasers to the beam combiner, the plurality of laser beam turning mechanisms secured to the housing.

26. The laser system as set forth in Claim 25 wherein the plurality of laser beam turning mechanisms comprise at least one mirror.

27. The laser system as set forth in Claim 24 wherein the beam combiner comprises:

a polarization rotator for rotating the polarization of the output of at least one waveguide laser of the plurality of waveguide lasers with respect to the remaining waveguide lasers; and

a polarizer for receiving the output of the plurality of waveguide lasers and superimposing said outputs.

28. The laser system as set forth in Claim 27 wherein the polarization rotator comprises at least one mirror.

29. The laser system as set forth in Claim 28 wherein the at least one mirror comprises three mirrors.

30. The laser system as set forth in Claim 28 wherein the at least one mirror comprises at least four mirrors wherein at least two of the at least four mirrors include a thin film quarter wave coating.

31. The laser system as set forth in Claim 27 wherein the polarizer comprises a thin film polarizer.

32. The laser system as set forth in Claim 24 further comprising a laser beam shaping mechanism for shaping the output of the plurality of waveguide lasers.

33. The laser system as set forth in Claim 25 wherein the plurality of laser beam turning mechanisms include a polarization rotator.

34. The laser system as set forth in Claim 24 wherein the beam combiner comprises at least one frequency selective mirror for receiving a first laser beam at a first frequency and receiving a second laser beam at a second frequency and superimposing first and second laser beams.

35. A laser system comprising:

a plurality of waveguide lasers; and

a beam combiner including a frequency selective mirror for superimposing the output of the plurality of waveguide lasers.

36. The laser system as set forth in Claim 35 further comprising a totally reflecting mirror for receiving a laser beam from a first waveguide laser and directing the laser beam to the frequency selective mirror.

37. The laser as set forth in Claim 4 further comprising a laser beam turning mechanism secured to the housing for receiving the output of the plurality of waveguides and redirecting the output.

38. The laser as set forth in Claim 4 further comprising a laser beam shaping mechanism for receiving the output of the plurality of waveguides and shaping the output.

39. The laser as set forth in Claim 1 further comprising a laser beam shaping mechanism for receiving the output of the plurality of waveguides and shaping the output.

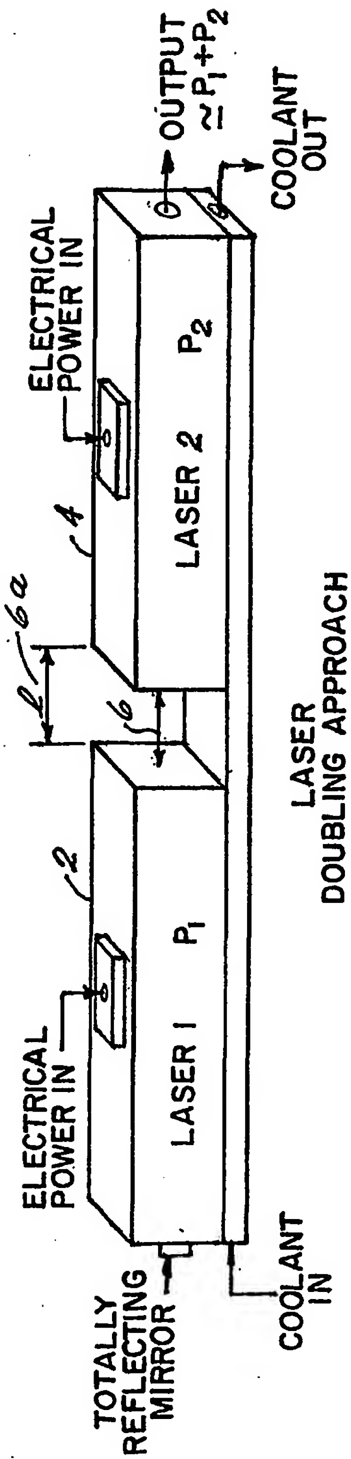


FIG. 1
(PRIOR ART)

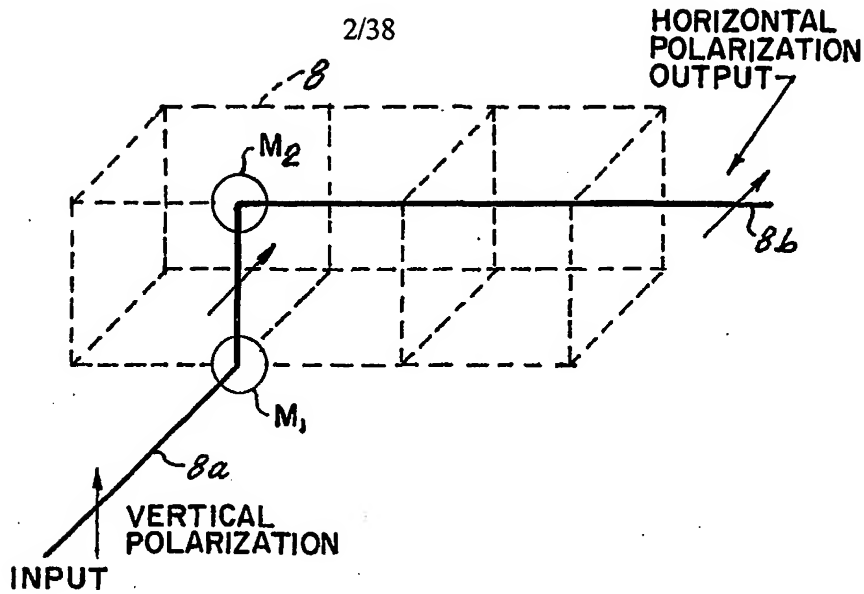


FIG. 2A
(PRIOR ART)

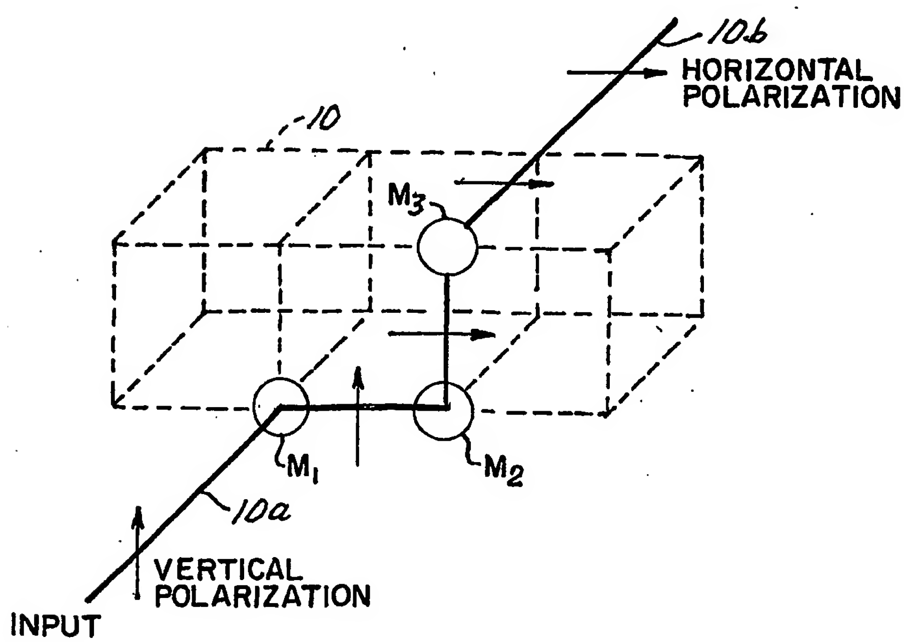


FIG. 2B
(PRIOR ART)

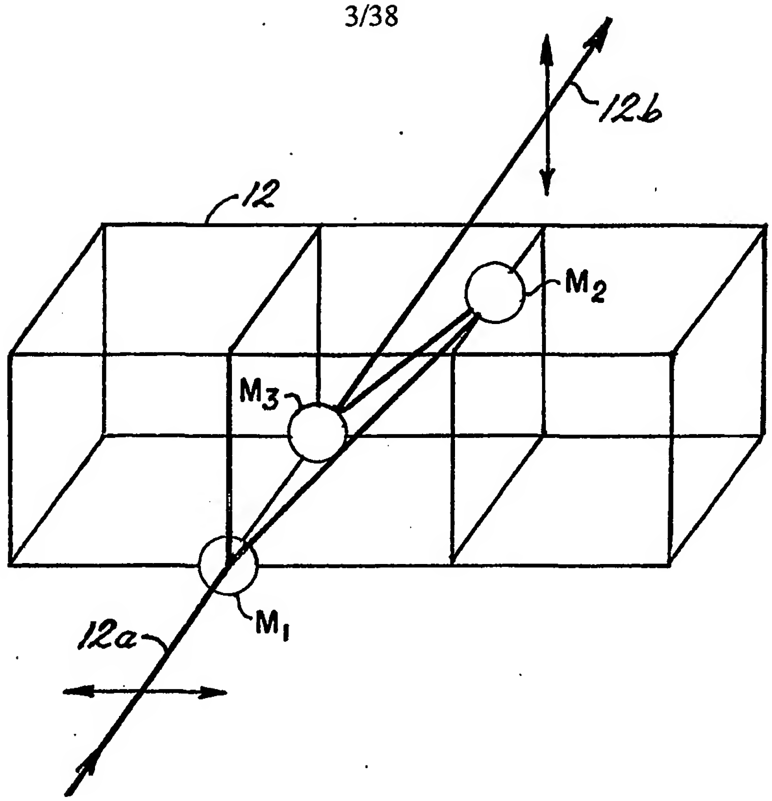


FIG. 3A
(PRIOR ART)

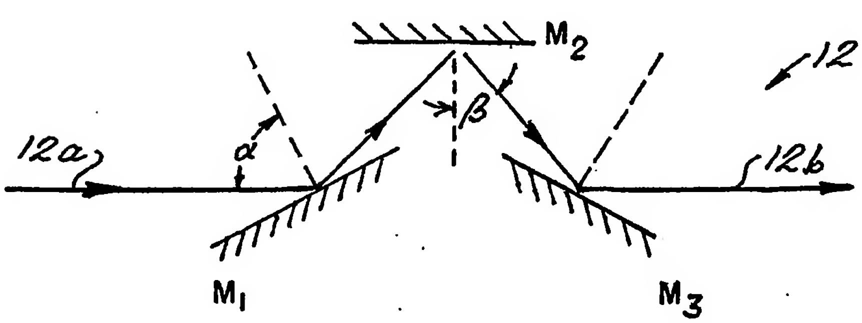


FIG. 3B
(PRIOR ART)

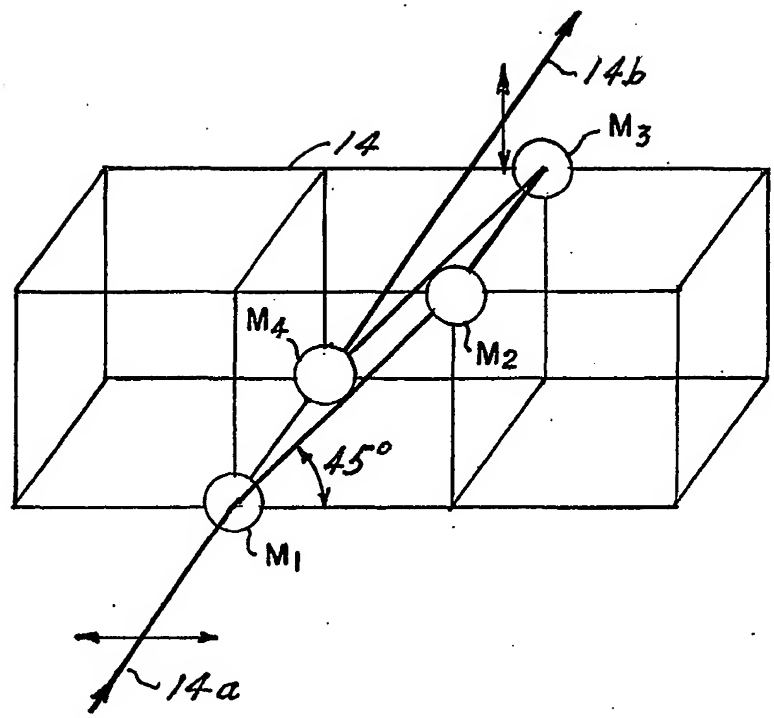


FIG. 4A
(PRIOR ART)

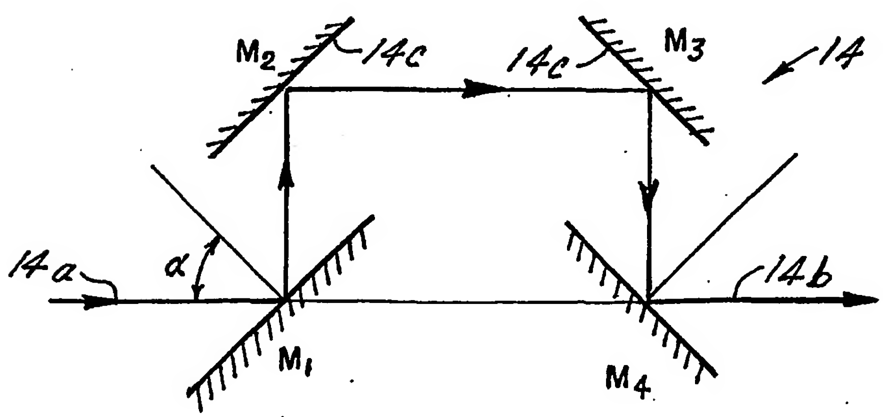


FIG. 4B
(PRIOR ART)

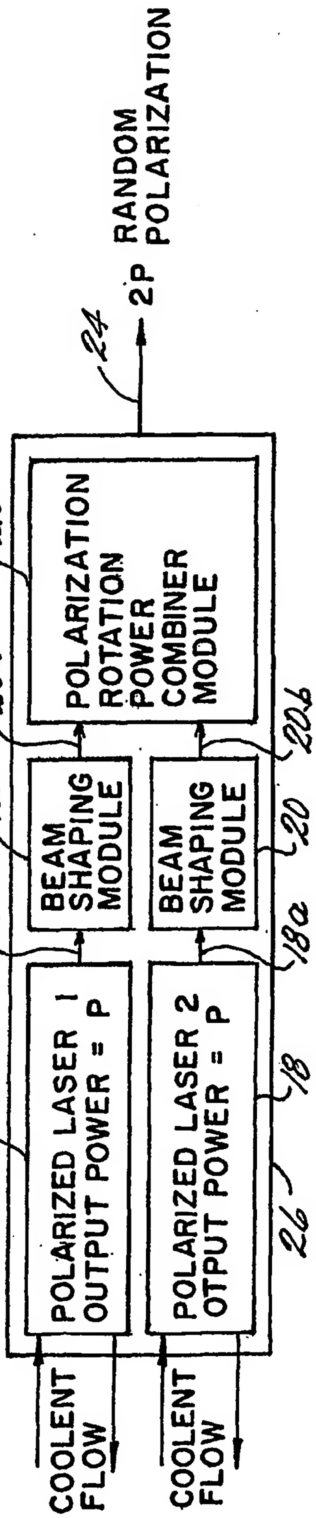


FIG. 5A
(PRIOR ART)

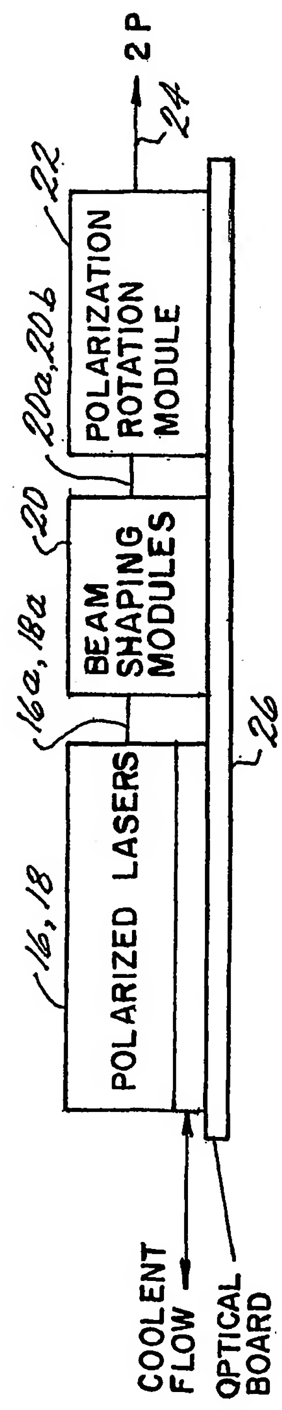


FIG. 5B
(PRIOR ART)

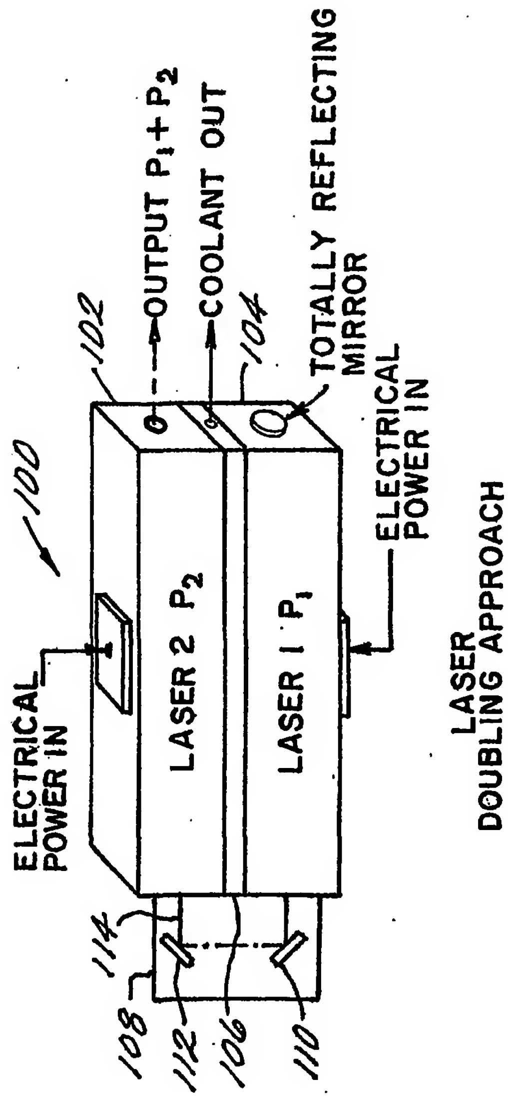
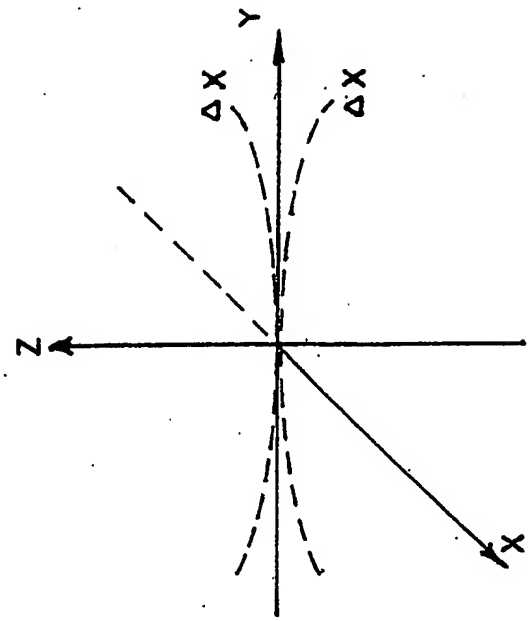
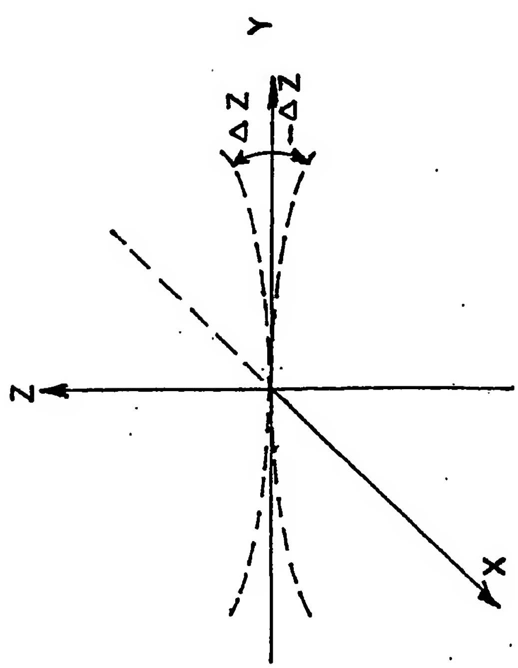

100
102
OUTPUT $P_1 + P_2$
COOLANT OUT
104
TOTALLY REFLECTING MIRROR
ELECTRICAL POWER IN
LASER 2 P_2
LASER 1 P_1
ELECTRICAL POWER IN
LASER DOUBLING APPROACH
114
108
112
106
110

FIG. 6A



VIBRATION IN XY PLANE
(LATERAL BENDING)

FIG. 6C



VIBRATION IN YZ PLANE
(VERTICAL BENDING)

FIG. 6B

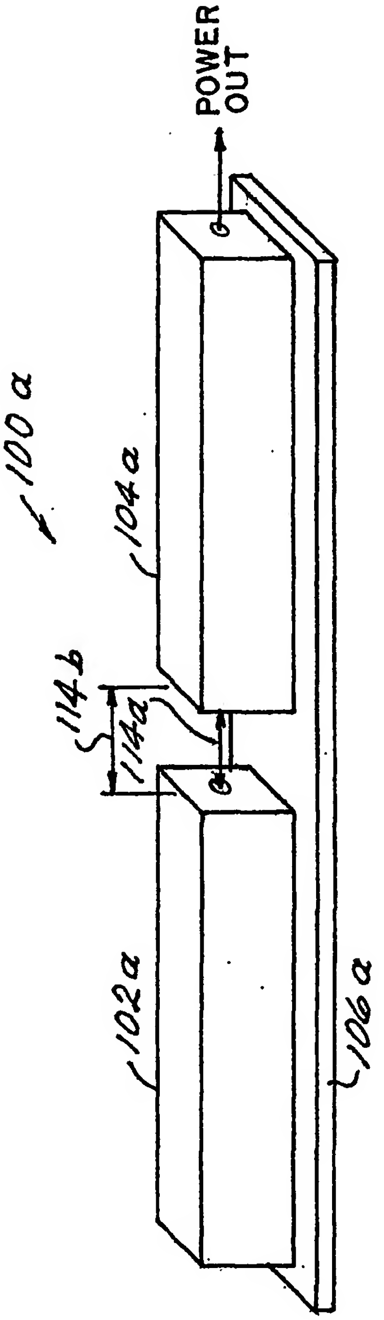
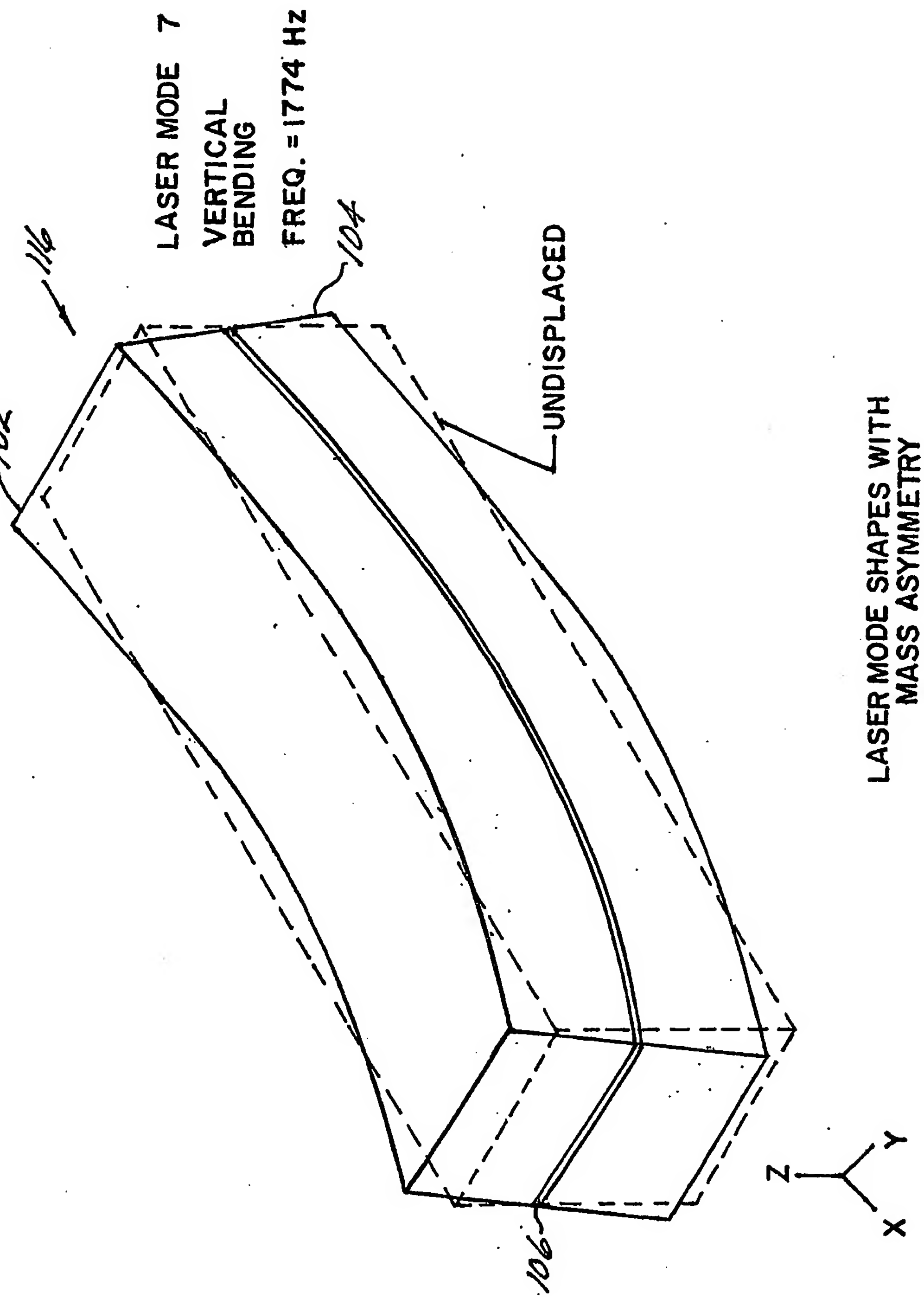
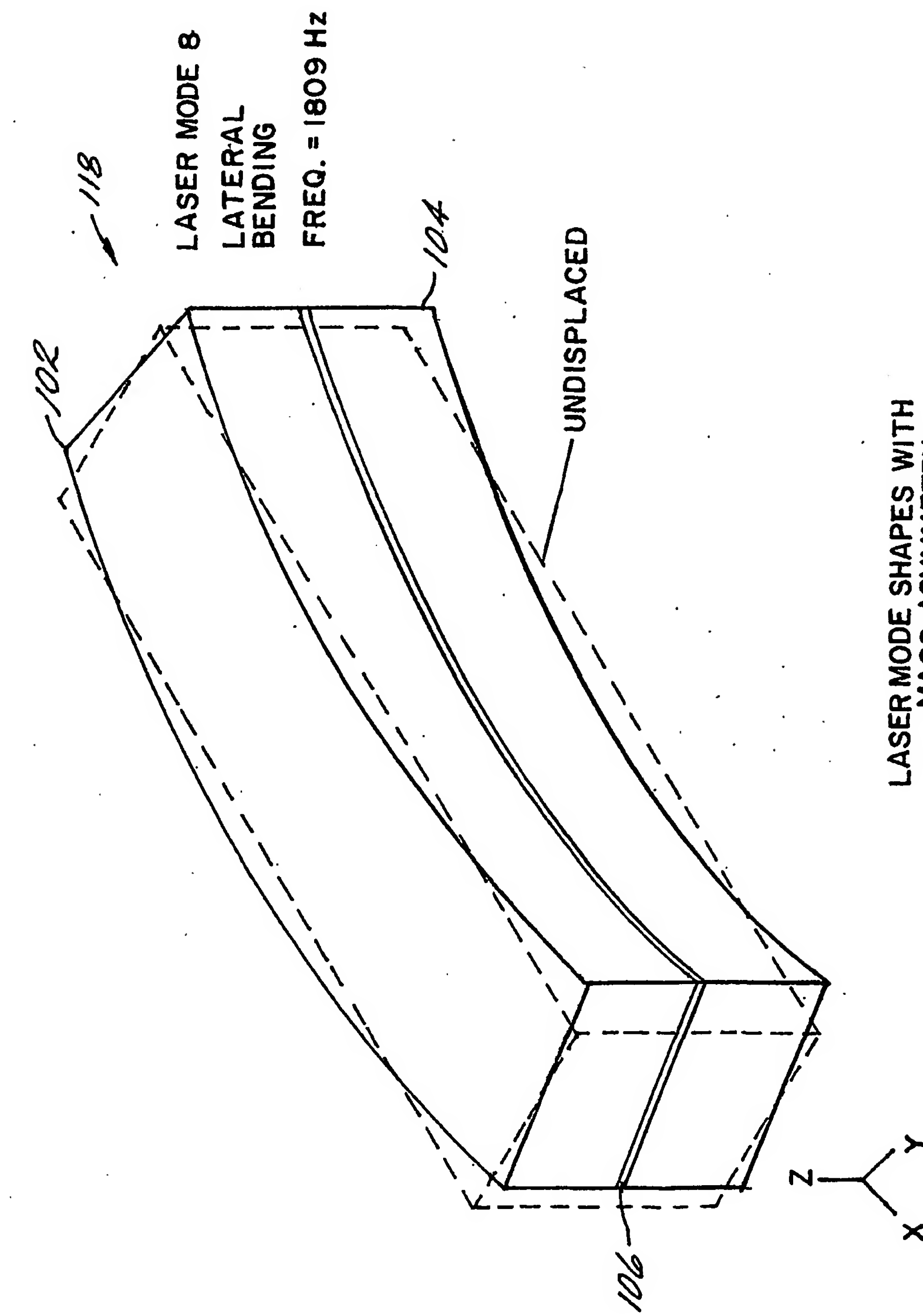


FIG. 6D



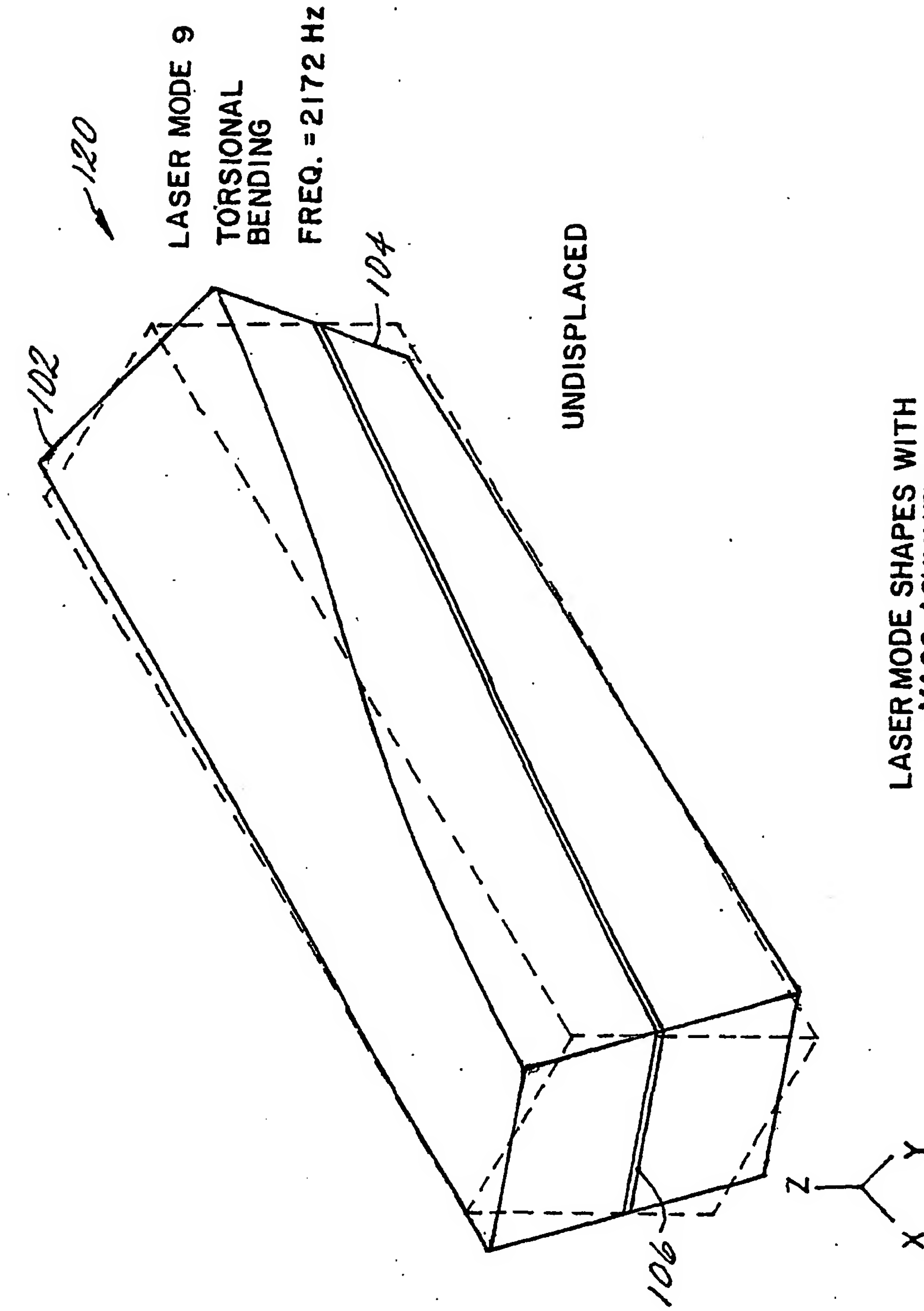
LASER MODE SHAPES WITH MASS ASYMMETRY

FIG. 7A



LASER MODE SHAPES WITH MASS ASYMMETRY

FIG. 7B



LASER MODE SHAPES WITH
MASS ASYMMETRY

FIG. 7C

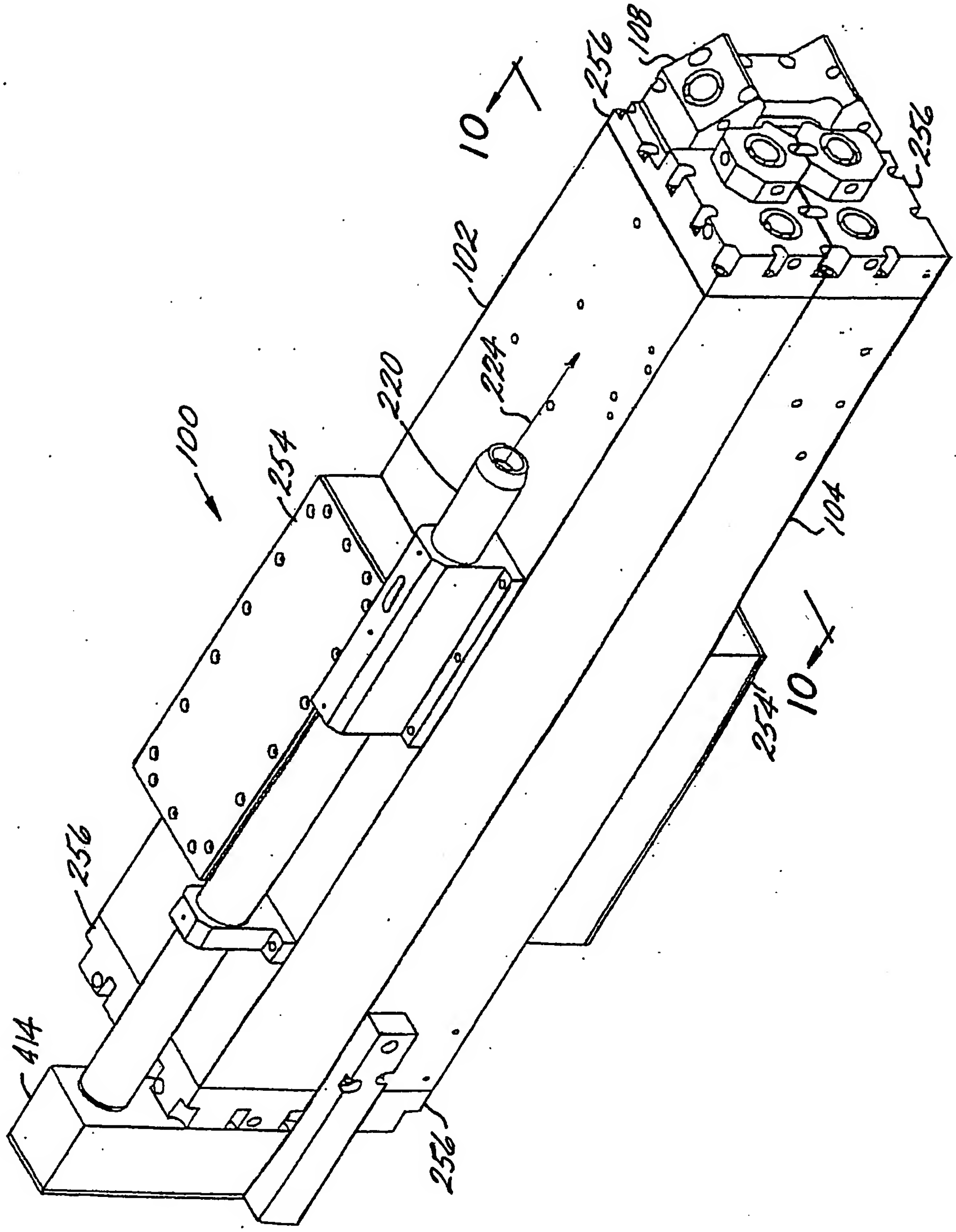


FIG. 8

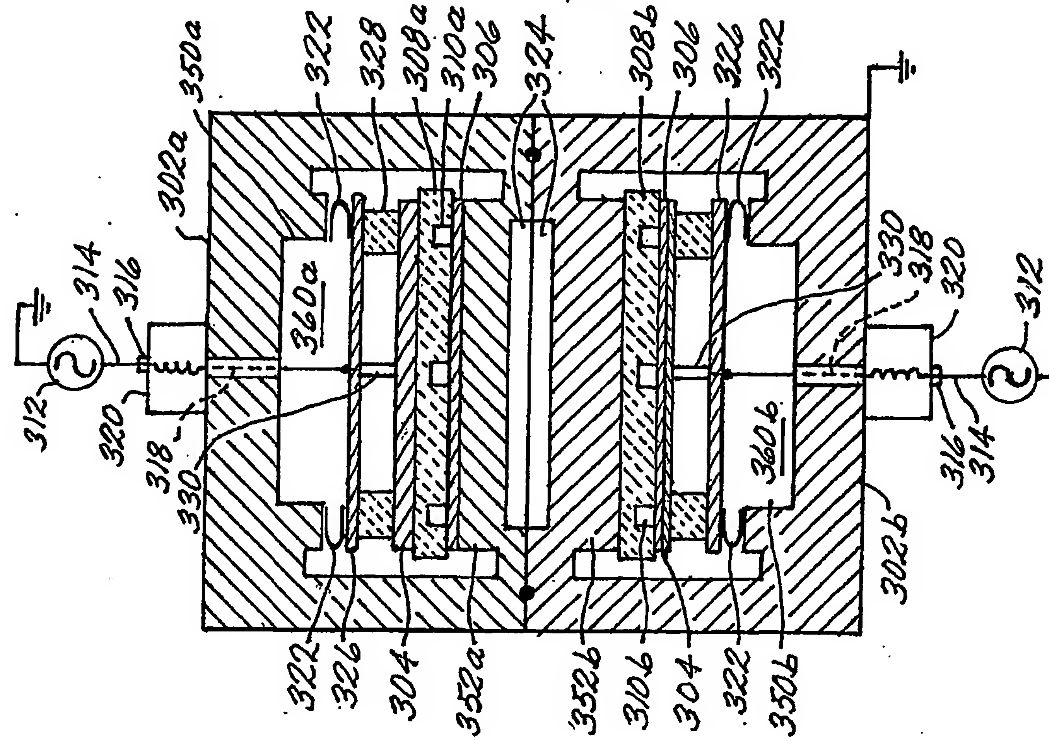


FIG. 10

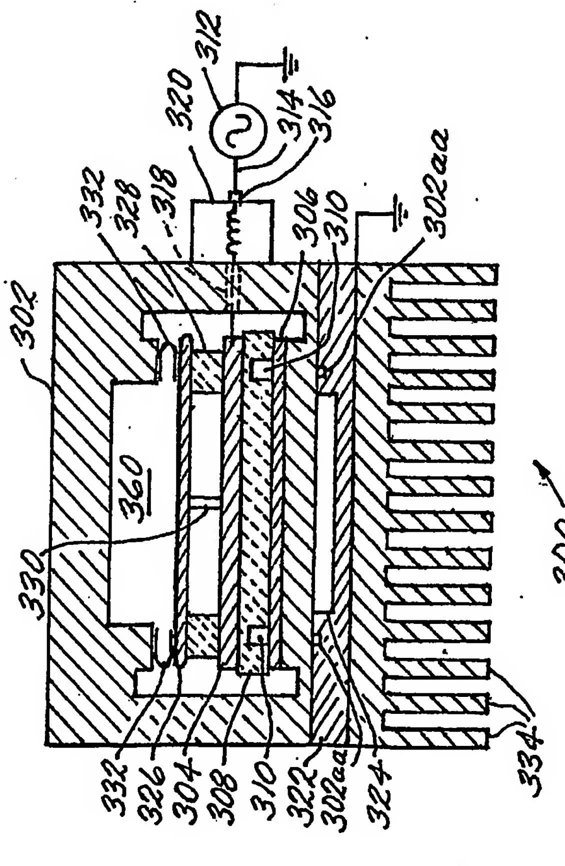


FIG. 9

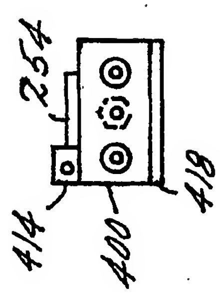


FIG. 11B

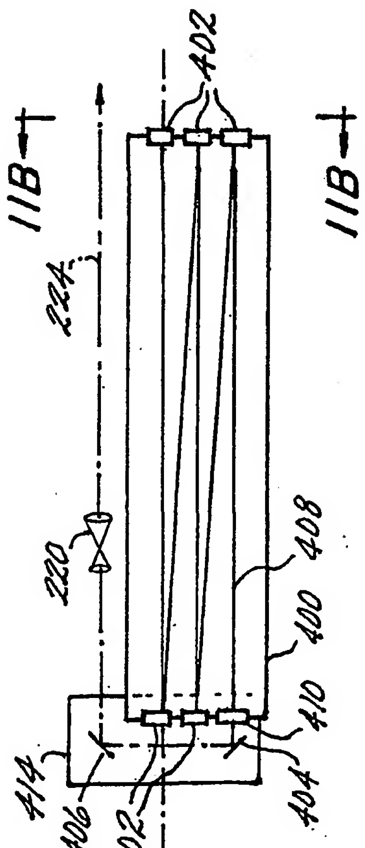


FIG. 11A

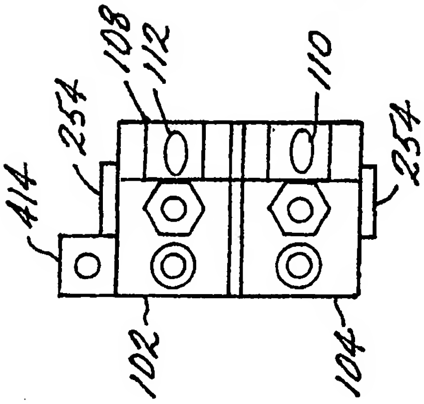


FIG. 12B

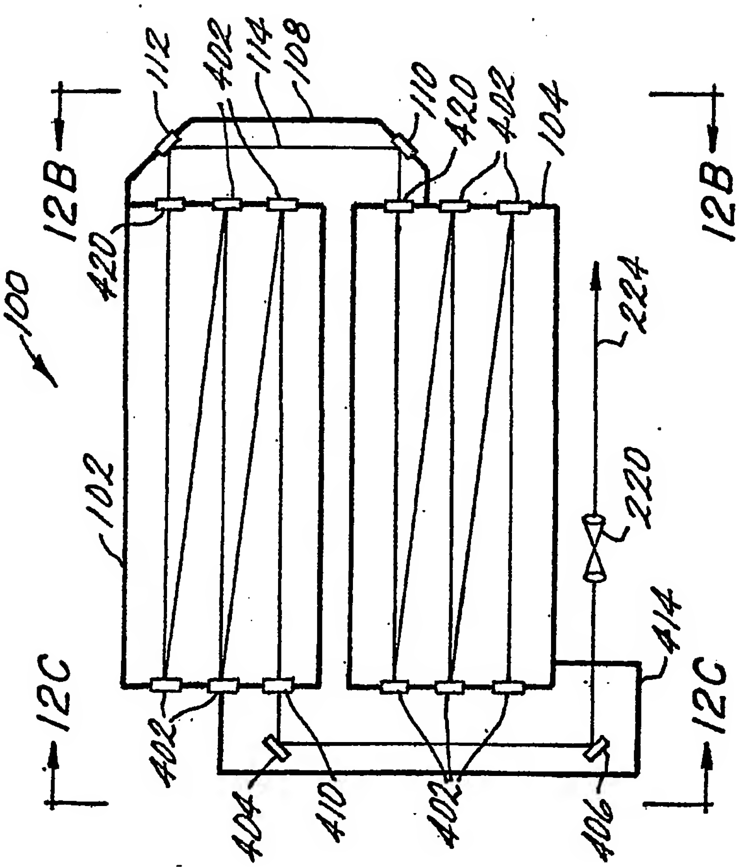


FIG. 12A

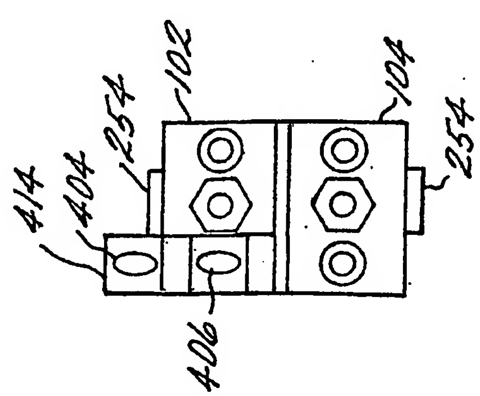


FIG. 12C

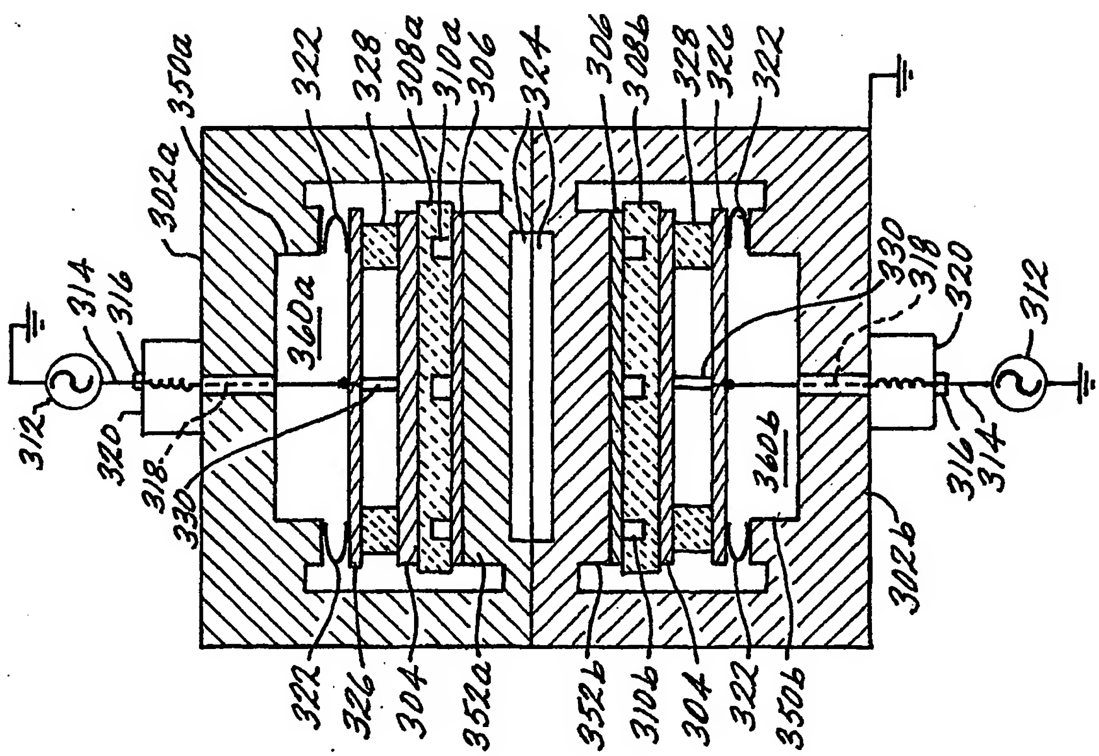

350a
302a
322
328
308a
310a
306
324
306
308b
328
326
322
360a
314
316
312
320
318
330
330
318
320
312
360b
316
314
302b
322
326
304
352a
352b
310b
304
322
350b

FIG. 13

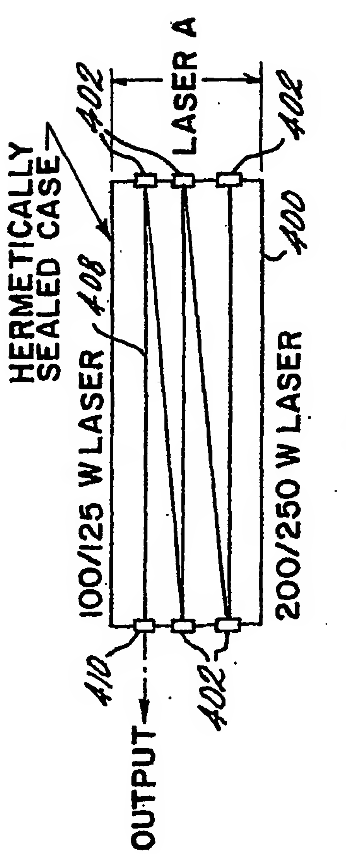


FIG. 14A

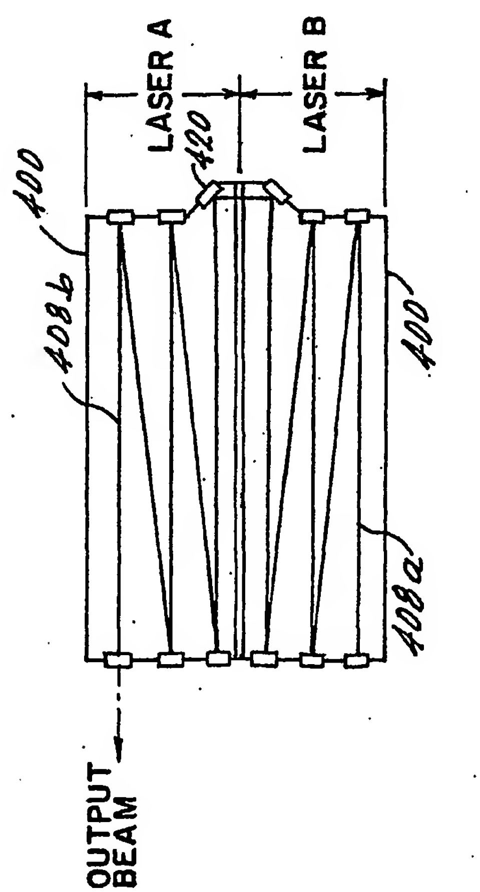


FIG. 14B

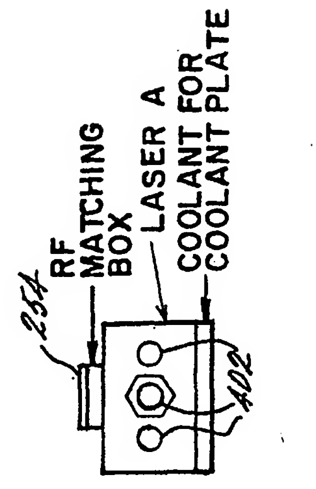


FIG. 14C

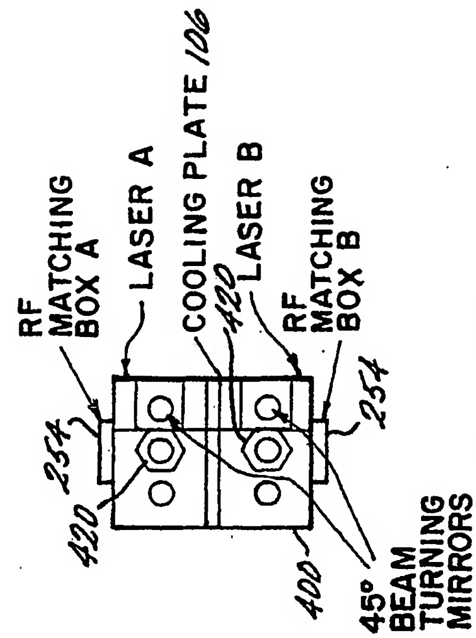


FIG. 14D

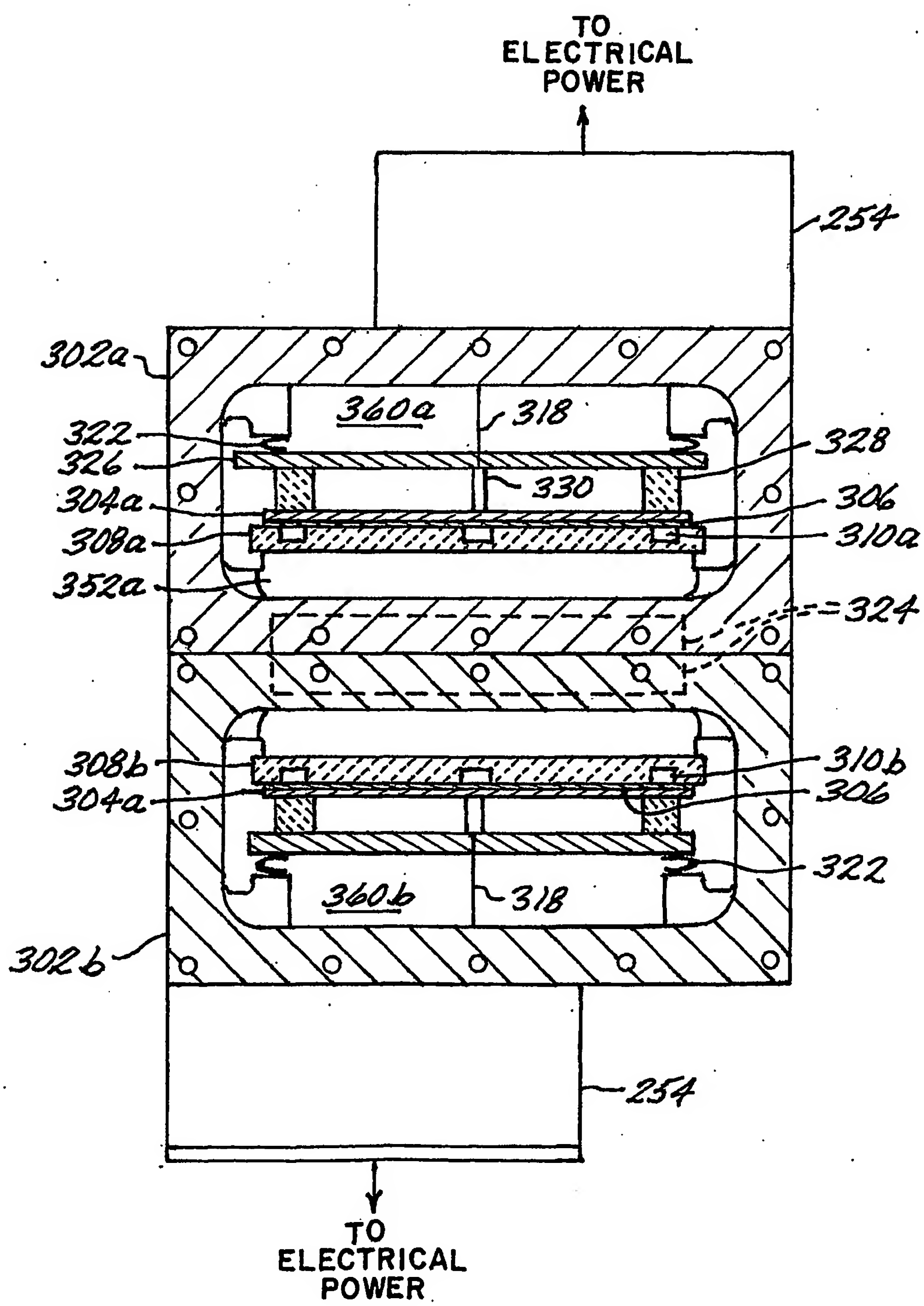

TO
ELECTRICAL
POWER
254
302a
360a
318
322
326
328
330
304a
306
308a
310a
352a
324
308b
310b
304a
306
322
360b
318
302b
254
TO
ELECTRICAL
POWER

FIG. 15

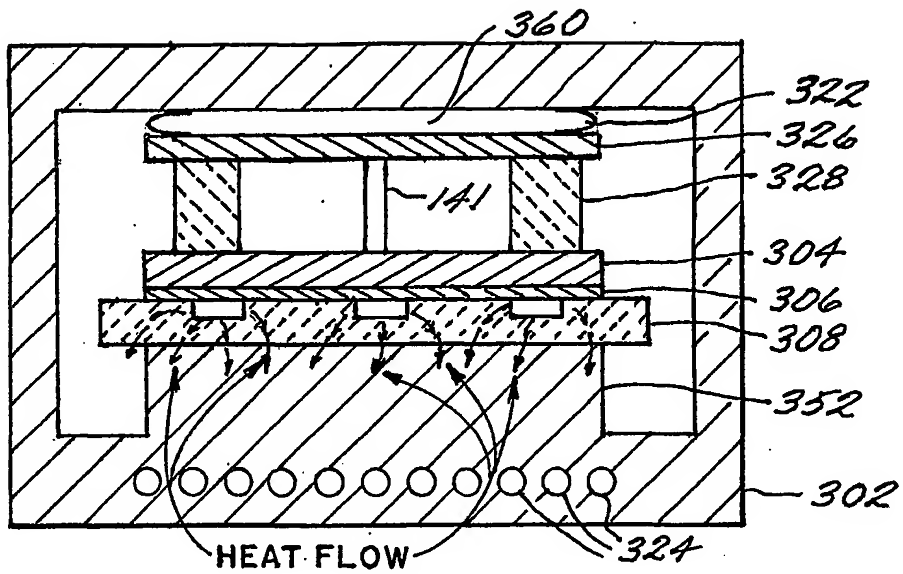


FIG. 16A

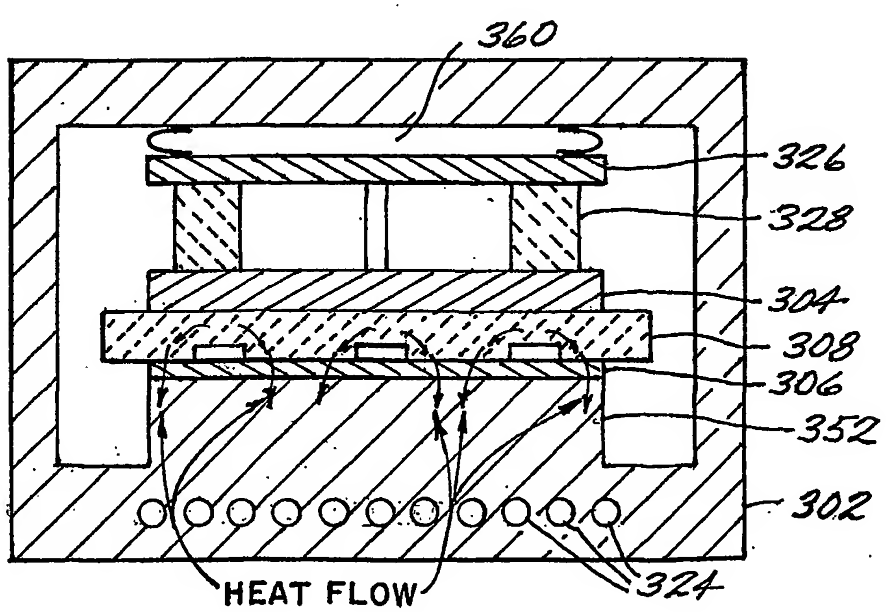


FIG. 16B

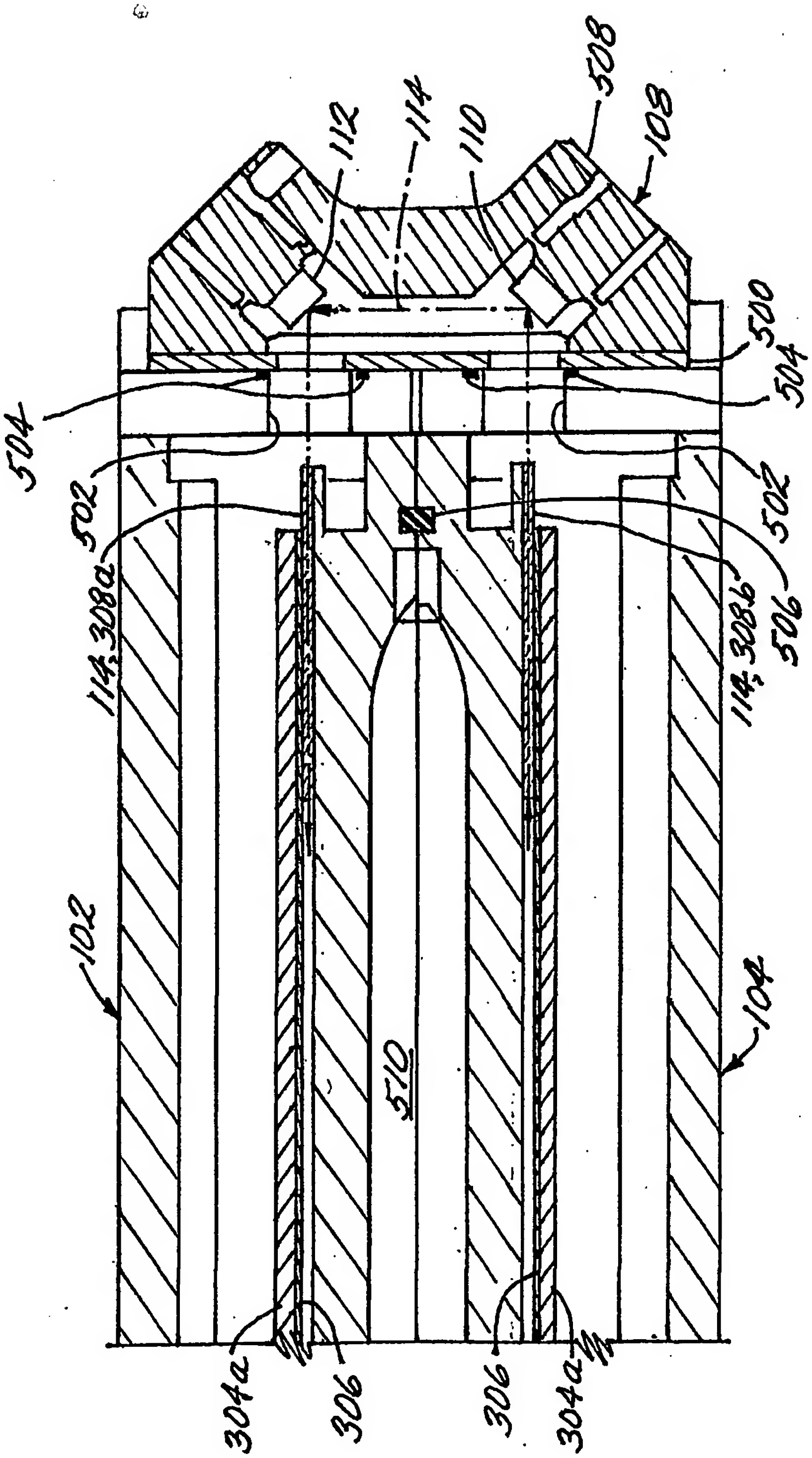

508
108
112
114
110
500
504
504
502
502
114,308a
114,308b
506
102
104
510
304a
306
306
304a

FIG. 17

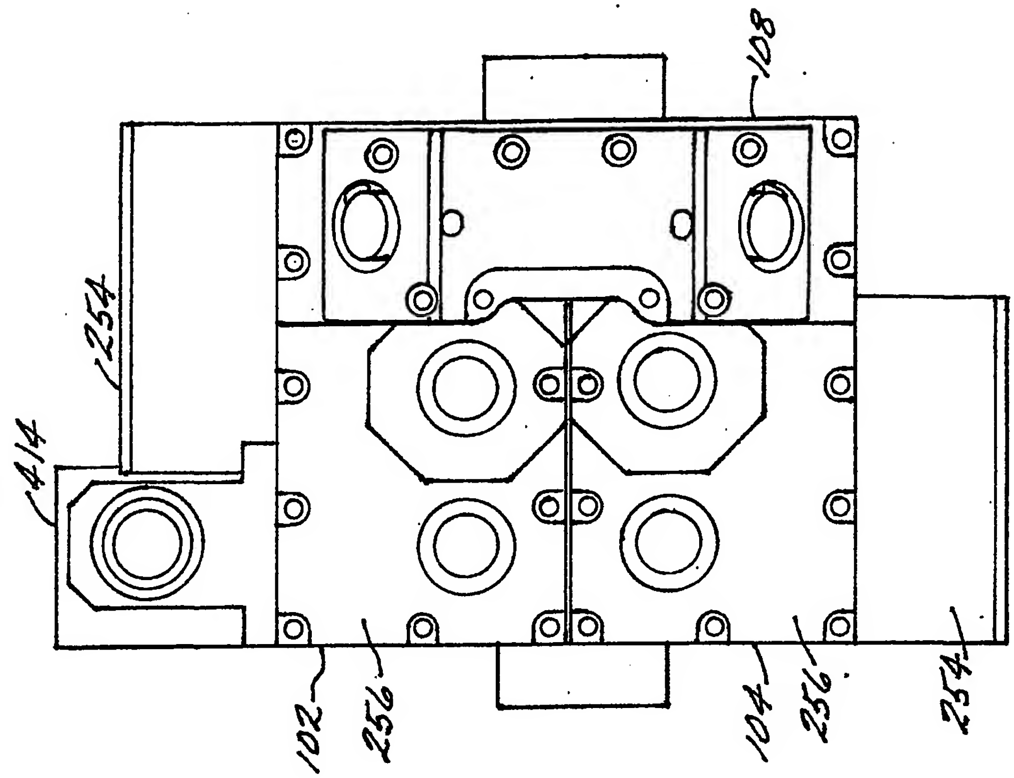


FIG. 18B

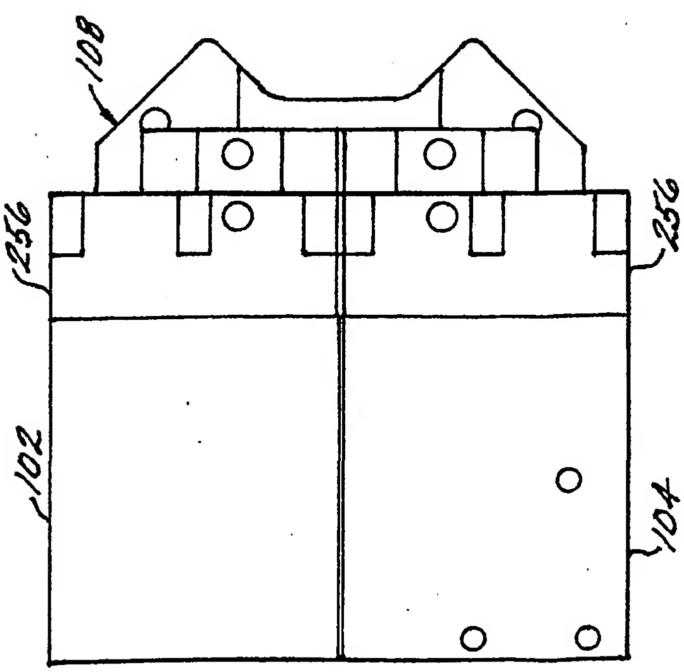


FIG. 18A

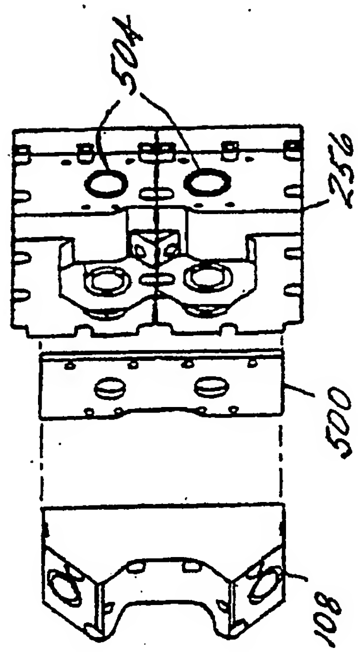


FIG. 19B

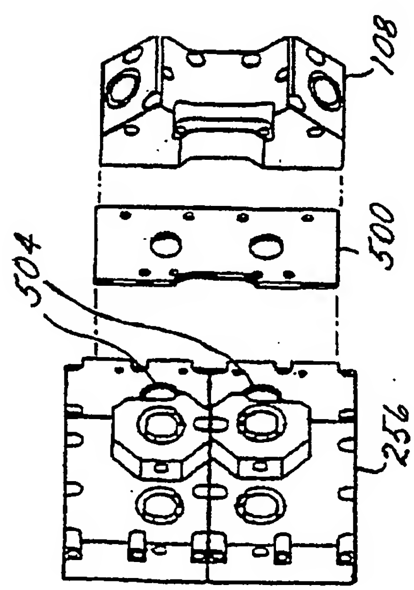


FIG. 19A

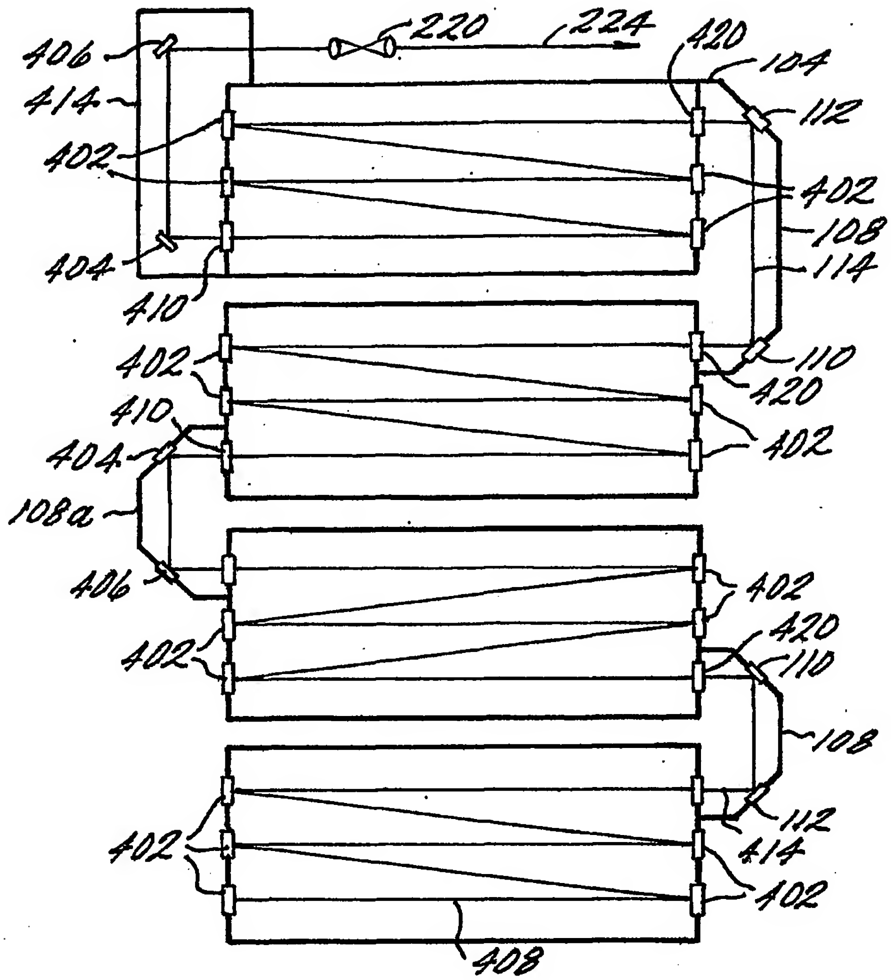


FIG. 20A

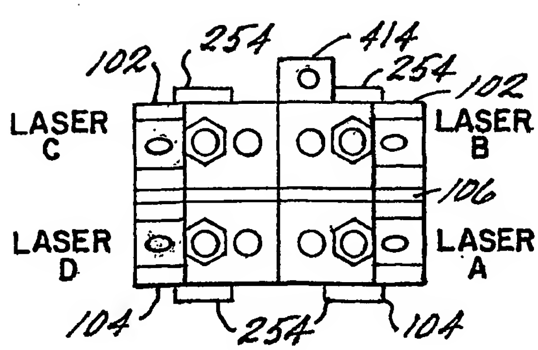


FIG. 20B

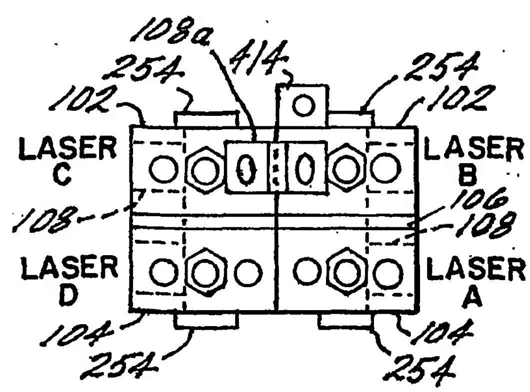


FIG. 20C

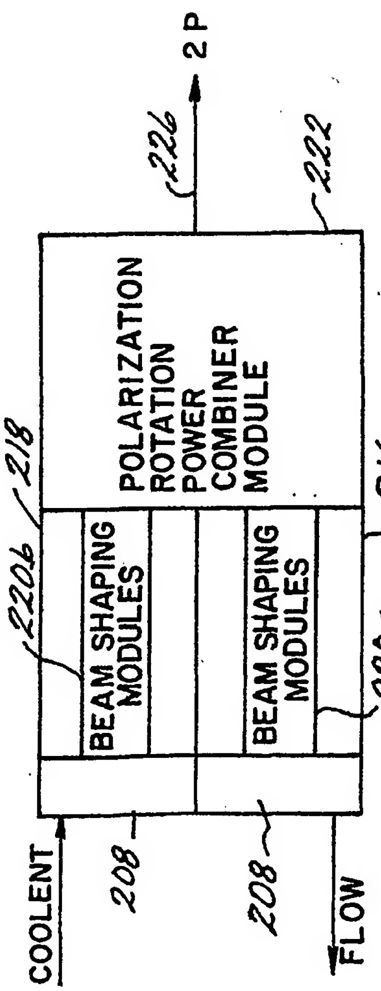


FIG. 21A

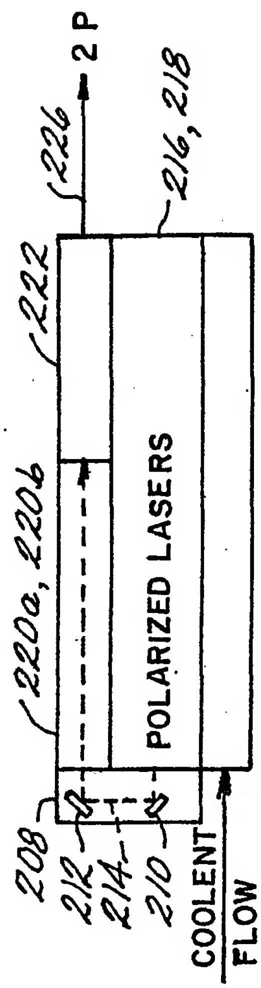


FIG. 21B

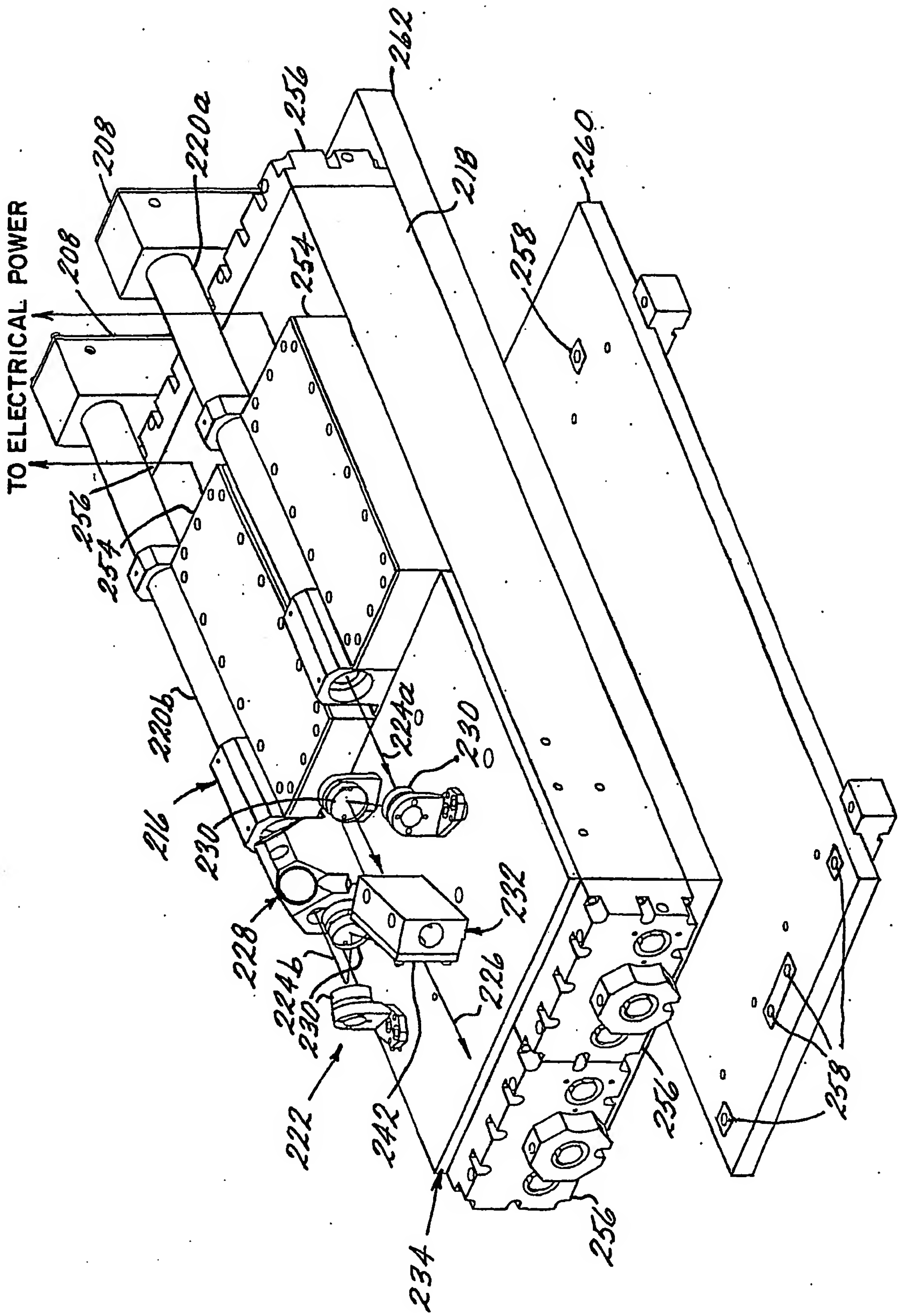

TO ELECTRICAL POWER
208
208
220a
256
262
254
218
260
258
256
254
220b
216
230
224a
230
228
232
224b
230
226
222
242
234
256
256
258

FIG. 22

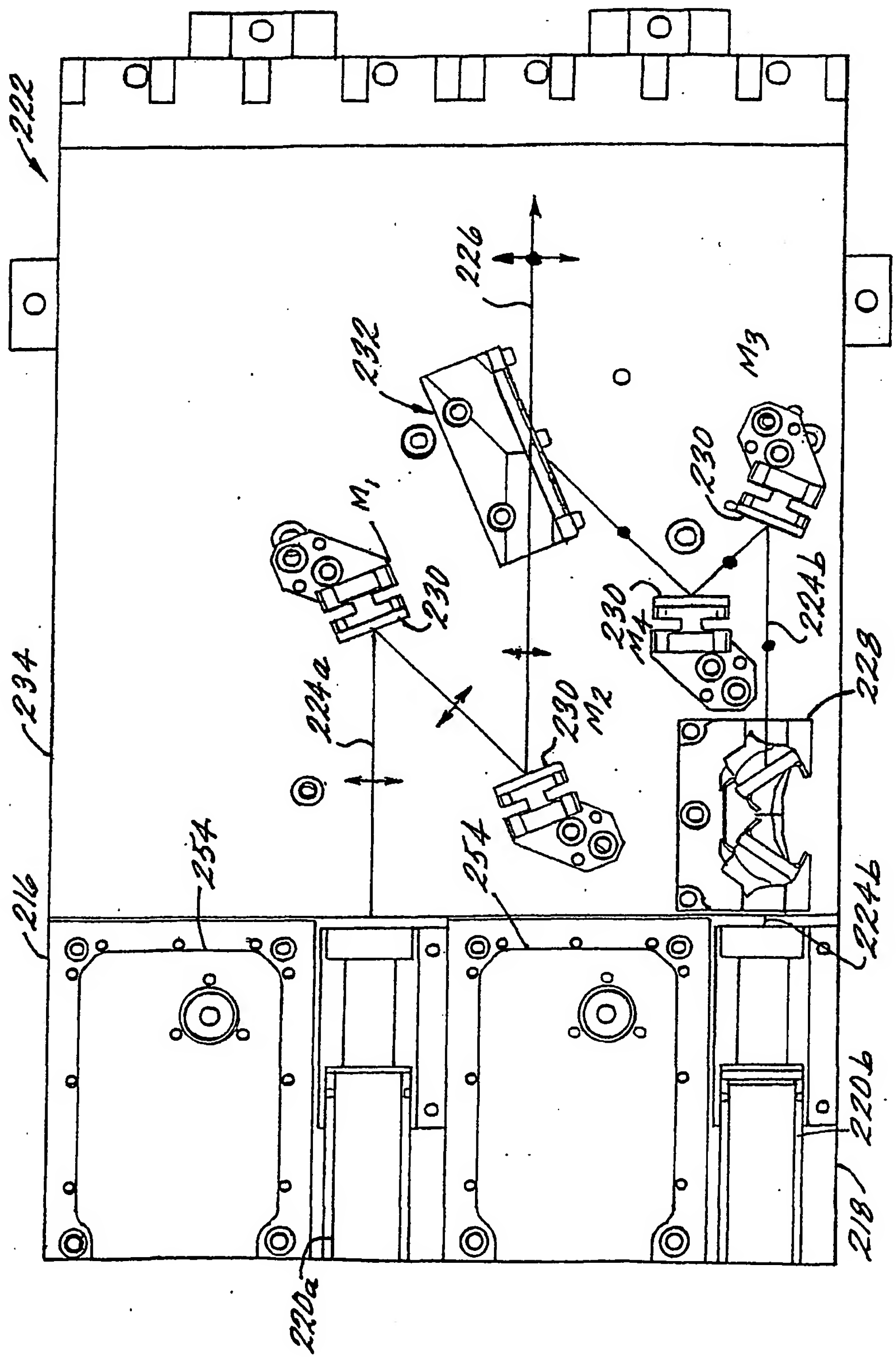

222
226
232
M3
230
M1
230
230
M4
224b
224a
230
M2
228
234
254
254
216
224b
220b
218
220a

FIG. 23A

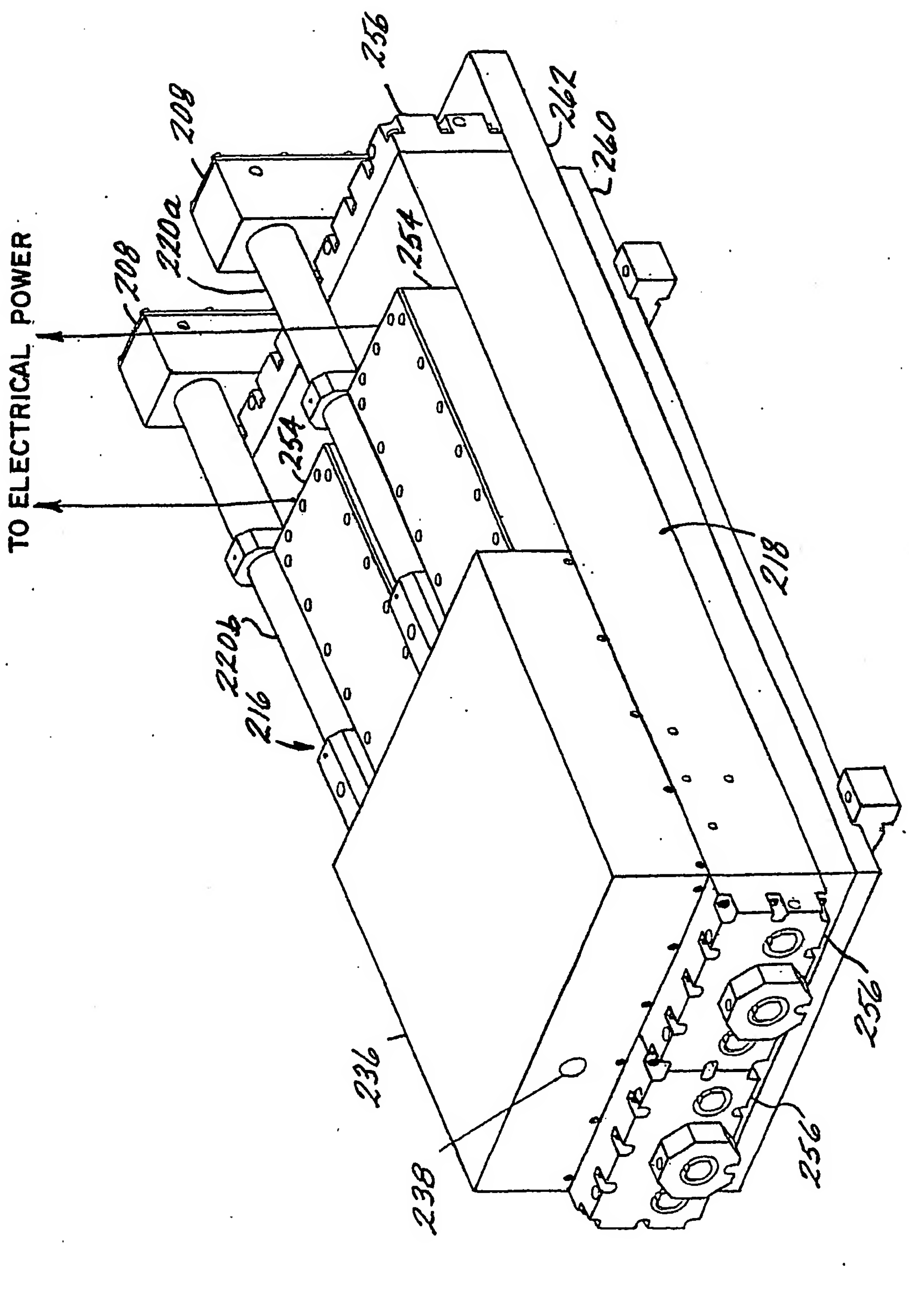

TO ELECTRICAL POWER
208
208
220a
256
262
260
254
254
218
220b
216
236
238
256
256

FIG. 23B

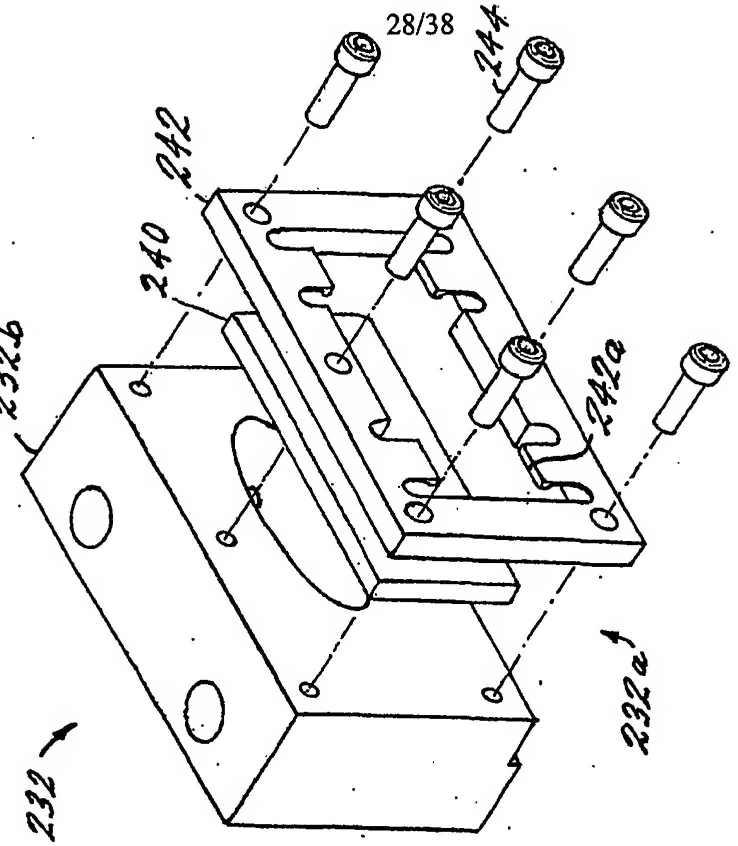


FIG. 24B

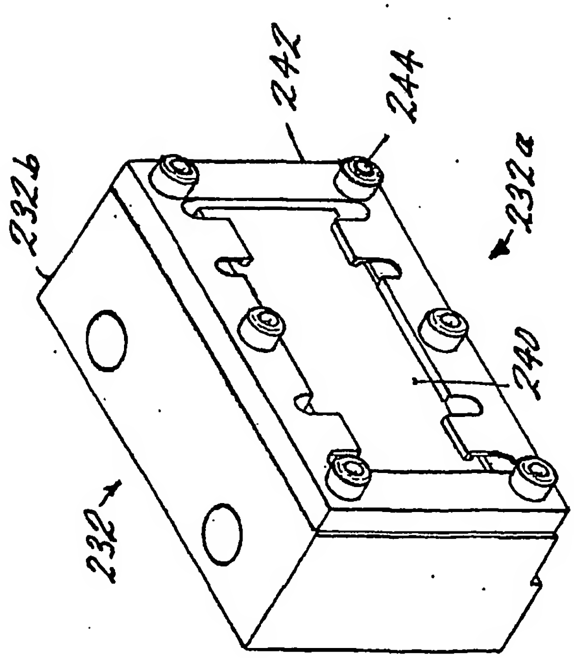


FIG. 24A

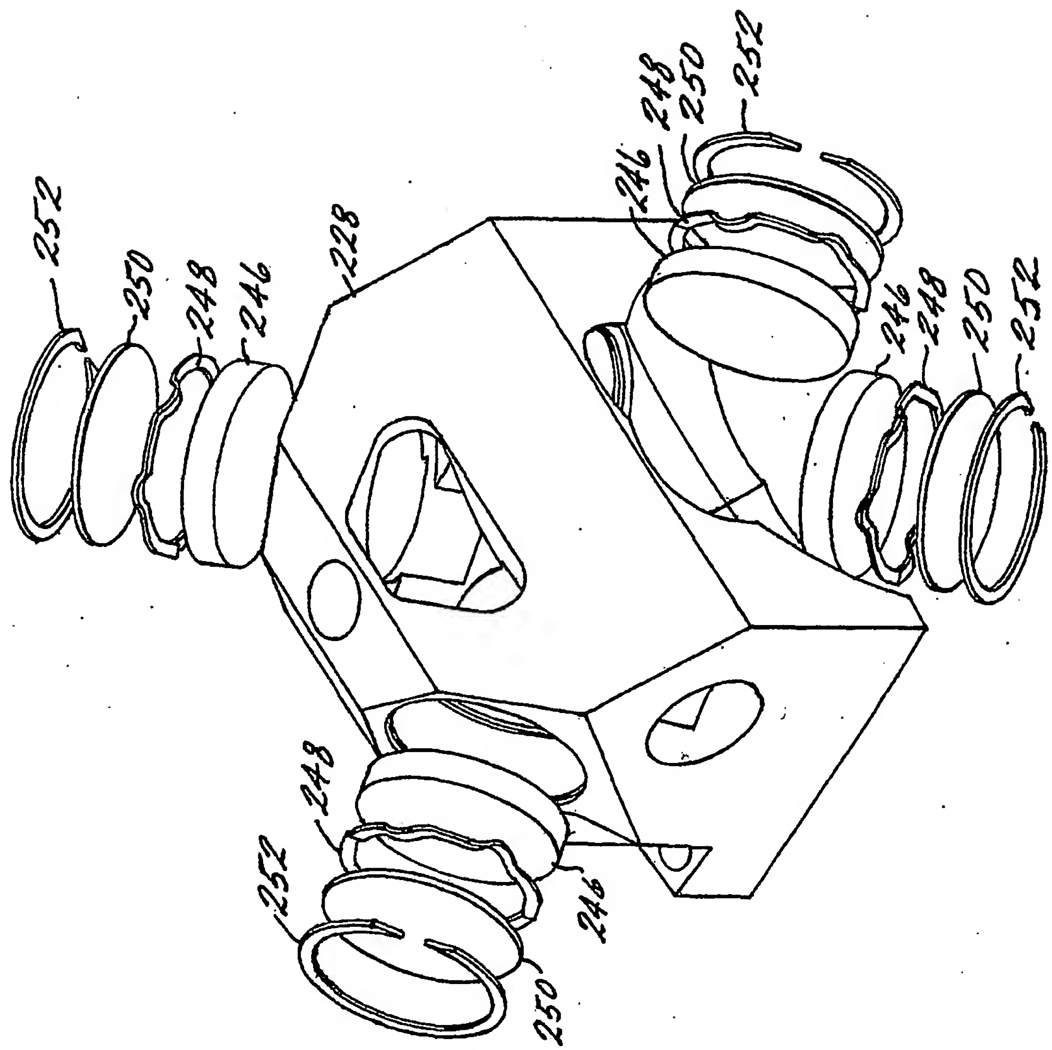

252
250
248
246
228
246
248
250
252
246
248
250
252
252
248
246
250

FIG. 25A

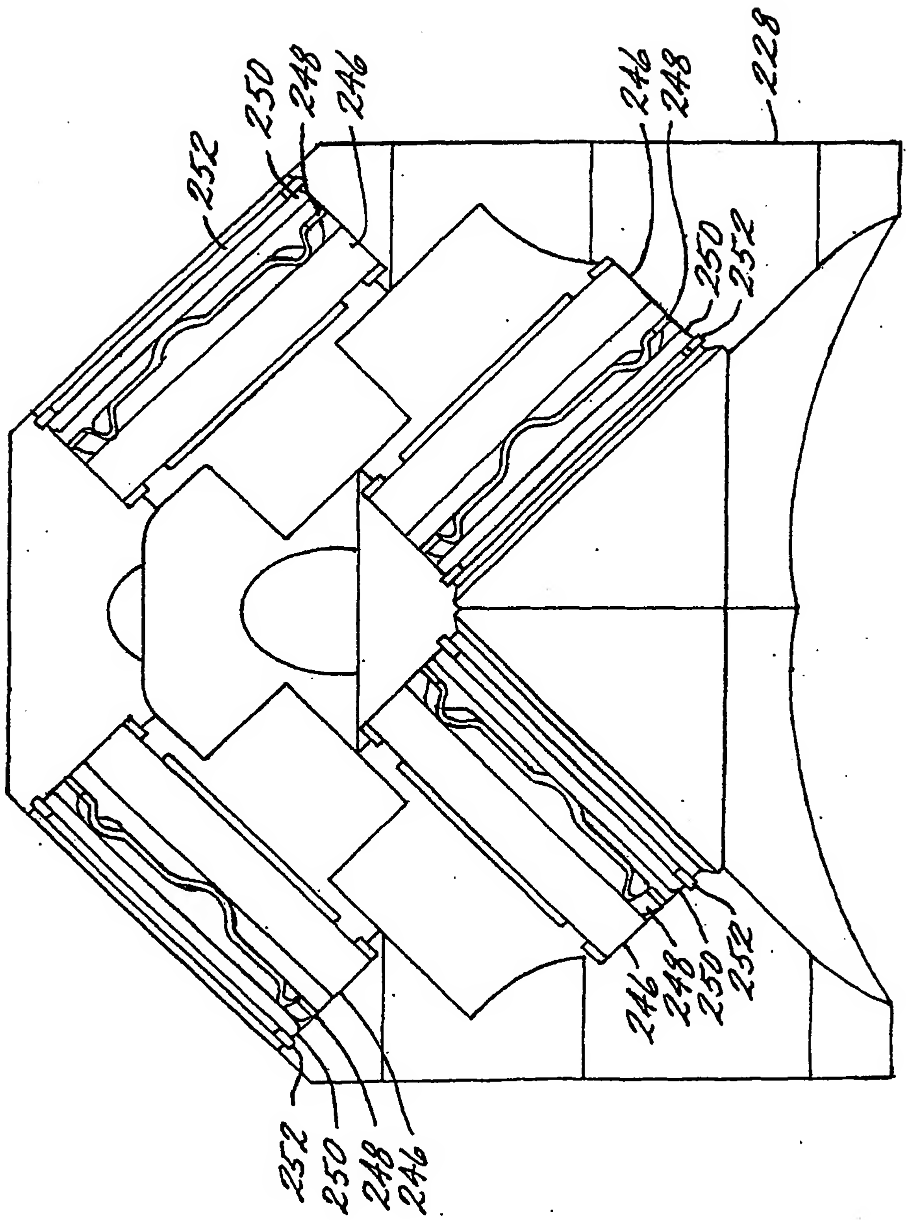

228
246
248
250
252
246
248
250
252
246
248
250
252
252
250
248
246

FIG. 25B

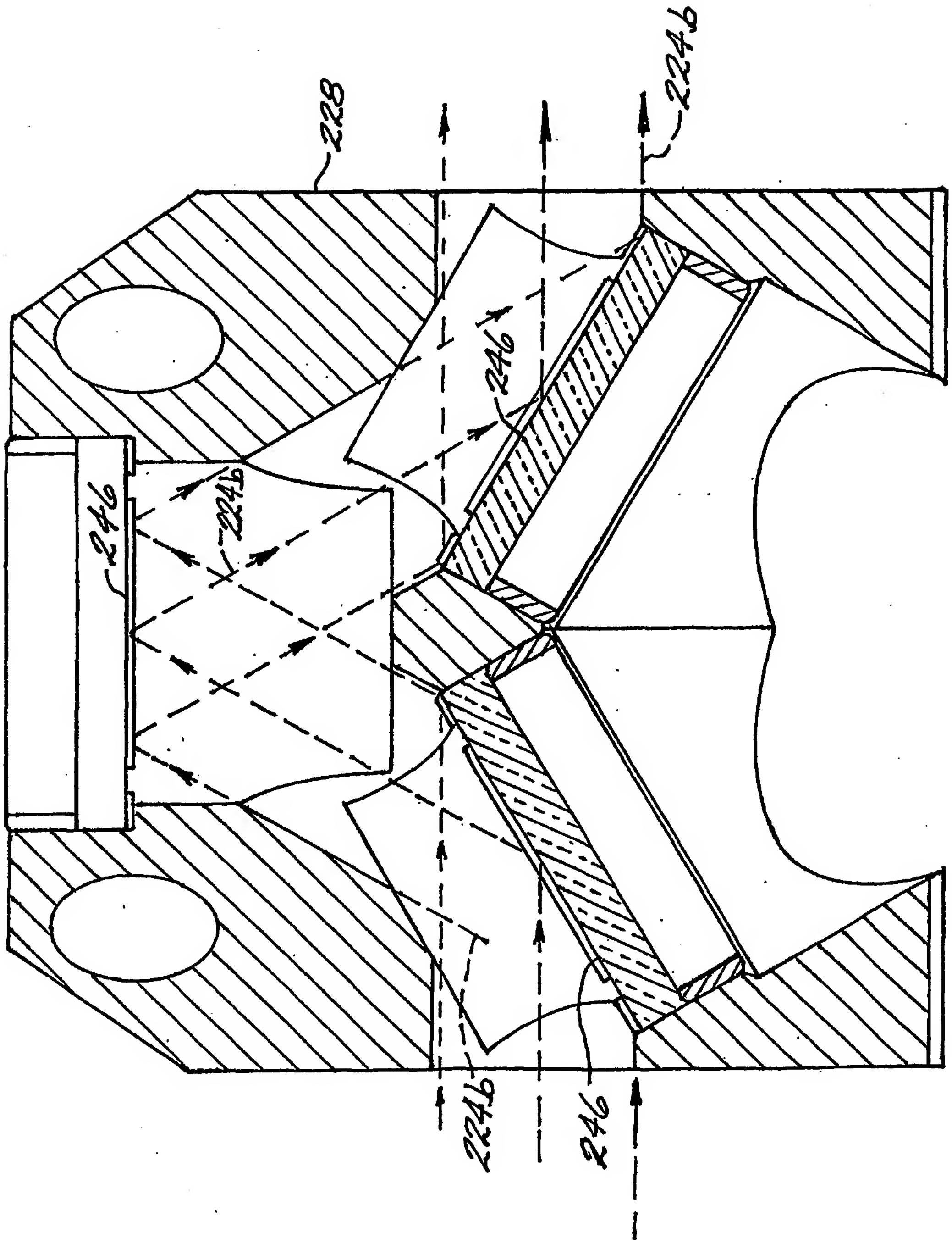


FIG. 25C

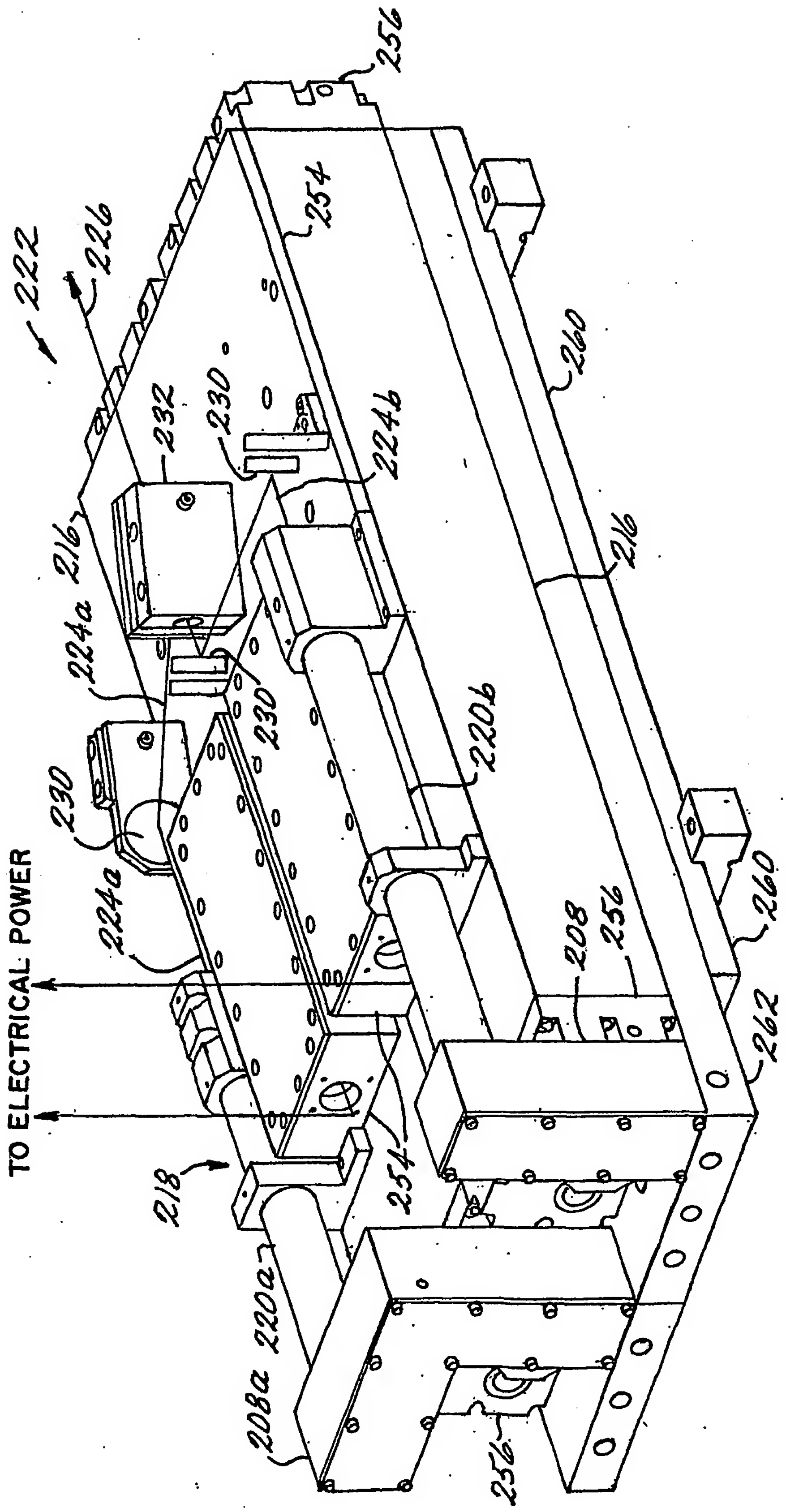

TO ELECTRICAL POWER
222
226
256
254
232
230
224b
216
224a
230
260
220b
208
256
262
218
254
220a
208a
256

FIG. 26

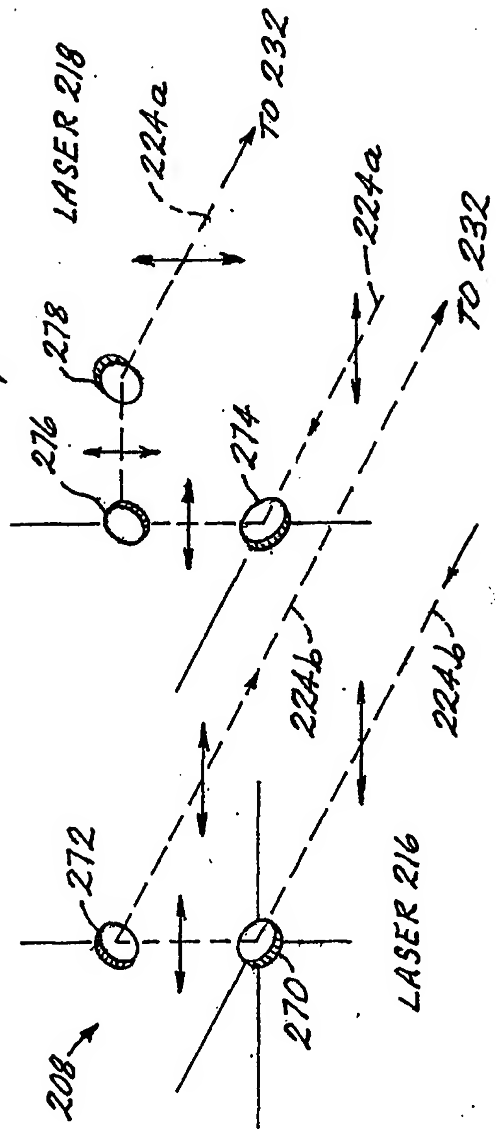

208a
278
276
274
LASER 218
224a
TO 232
224a
TO 232
224b
224b
272
270
208
LASER 216

FIG. 27

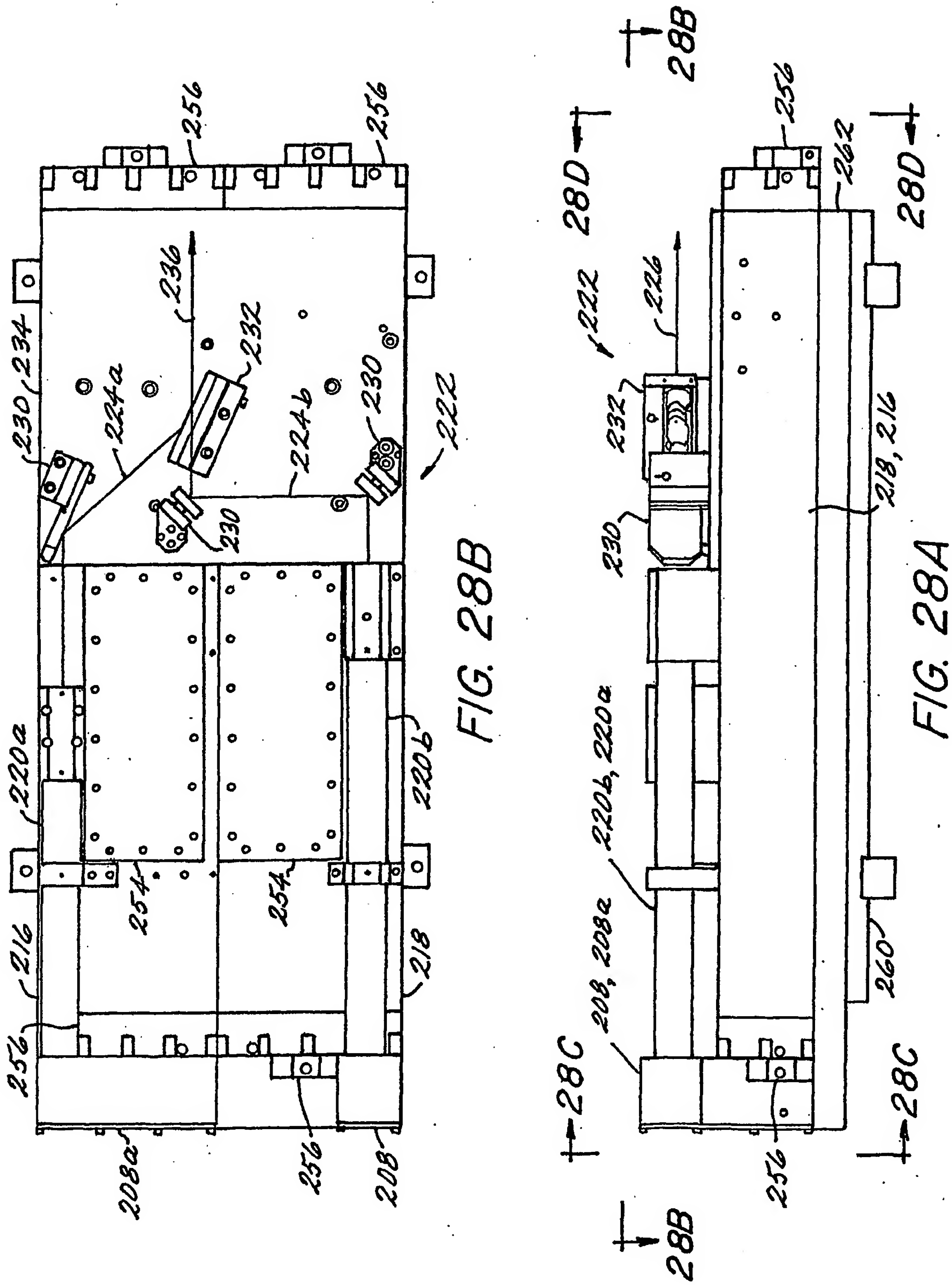


FIG. 28B

FIG. 28A

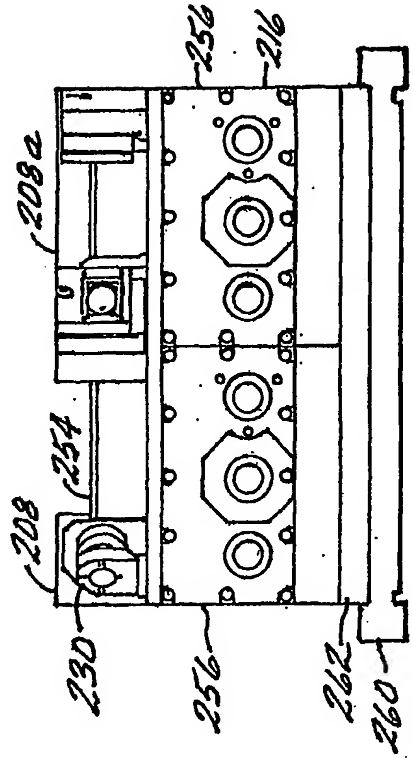


FIG. 28D

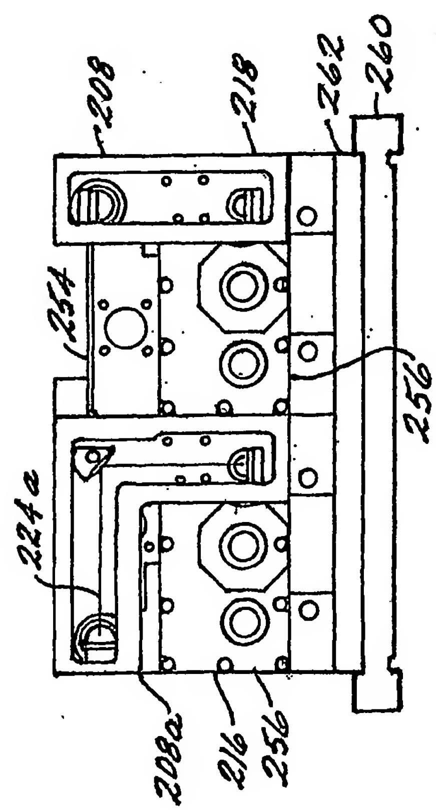


FIG. 28C

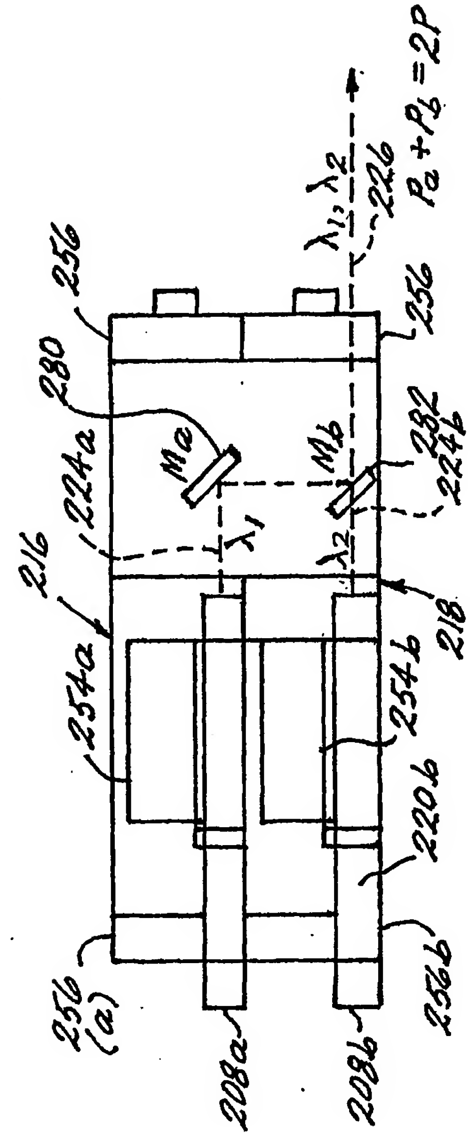


FIG. 30

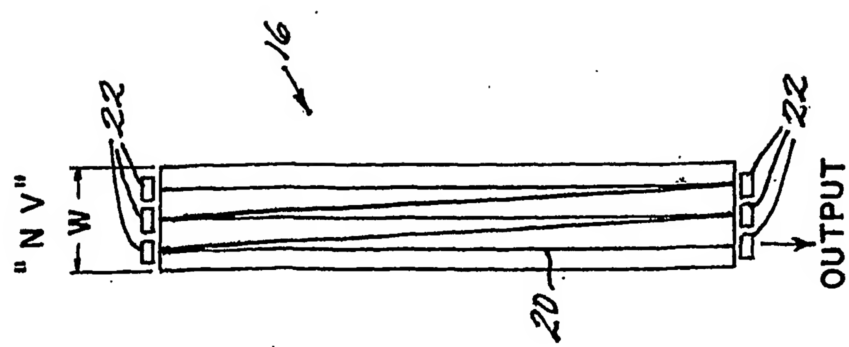


FIG. 29
(PRIOR ART)

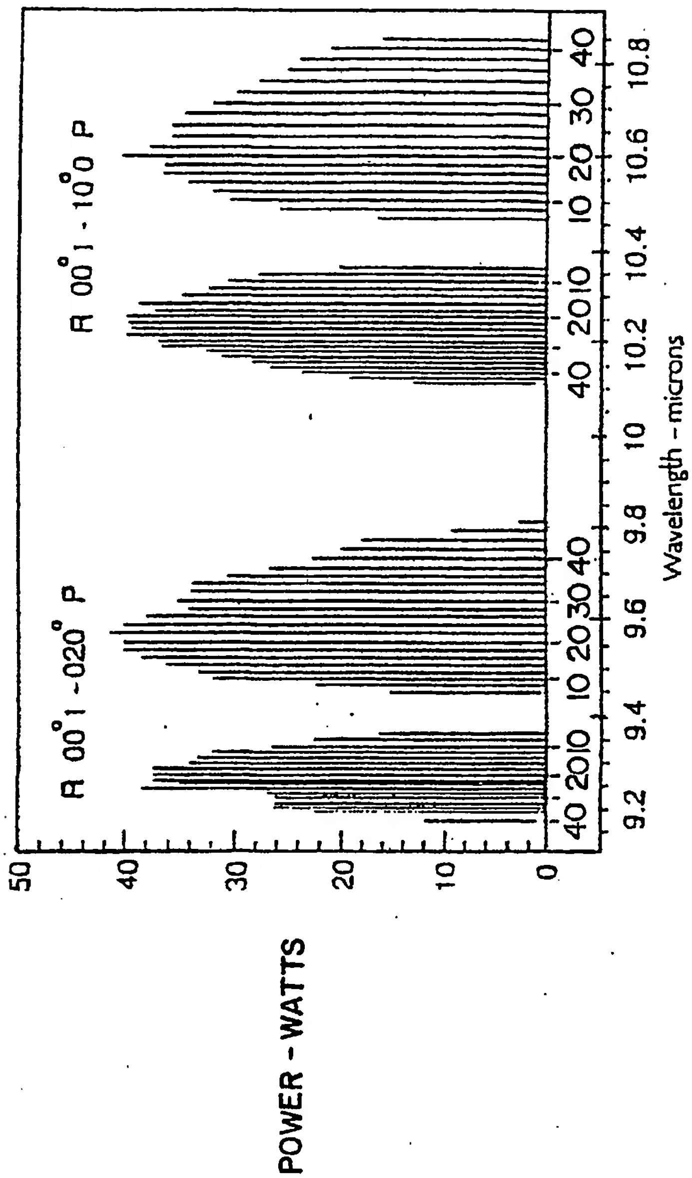


FIG. 31A

Representative output power for various transitions from 9.2 to 10.8 microns for CO_2 lasers

Rotational line	Wavelength (μ)	Power (watts)	Rotational line	Wavelength (μ)	Power (watts)	Rotational line	Wavelength (μ)	Power (watts)	Rotational line	Wavelength (μ)	Power (watts)
10P6	10.458	17.0	10R6	10.349	21.0	9P6	9.443	15	9R6	9.354	16.0
10P8	10.476	26.5	10R8	10.334	28.6	9P8	9.458	25.5	9R8	9.342	22.0
10P10	10.494	31.4	10R10	10.318	31.0	9P10	9.473	32.0	9R10	9.329	30.0
10P12	10.513	32.7	10R12	10.303	33.0	9P12	9.488	33.5	9R12	9.317	32.0
10P14	10.532	35.5	10R14	10.289	35.5	9P14	9.504	36.5	9R14	9.306	33.5
10P16	10.551	37.5	10R16	10.274	38.0	9P16	9.520	39.0	9R16	9.294	34.0
10P18	10.571	37.5	10R18	10,260	39.5	9P18	9.536	40.5	9R18	9.282	38.0
10P20	10.591	41.5	10R20	10.247	40.5	9P20	9.552	40.5	9R20	9.271.	38.0
10P22	10.611	39.0	10R22	10.233	40.5	9P22	9.569	42.0	9R22	9.261	35.0
10P24	10.632	37.1	10R24	10.220	40.1	9P24	9.588	40.5	9R24	9.250	39.5
10P26	10.653	36.8	10R26	10.207	40.5	9P26	9.604	38.5	9R26	9.240	27.0
10P28	10.675	35.5	10R28	10.195	37.5	9P28	9.621	36.			
10P30	10.696	33.2	10R30	10.182	37.0	9P30	9.639	35.5			
10P32	10.719	31.0	10R32	10.170	33.0	9P32	9.657	34.0			
10P34	10.741	29.0	10R34	10.159	31.5	9P34	9.675	34.0			
10P36	10.764	26.2	10R36	10.147	29.0	9P36	9.695	31.0			
10P38	10.787	24.8	10R38	10.136	27.0	9P38	9.714	27.0			
10P40	10.811	22.1	10R40	10.125	24.0	9P40	9.733	23.0			
10P42	10.835	17.	10R42	10.115	19.7	9P42	9.753	20.			
						9P44	9.773	18.			
						9P48	9.814	9			

FIG. 31B

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US01/14263

A. CLASSIFICATION OF SUBJECT MATTER
IPC(7) :H01S 3/10, 3/00, 3/08
US CL :372/93, 9, 38.05
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

U.S. : 372/93, 9, 38.05, 94, 81-82

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

NONE

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

NONE

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X --- Y	US 5,299,223 A (VAN DER WAL) 29 March 1994 (29.03.1994), Figs. and col. 3.	1-5, 23-39 -------- 6-22
Y	US 4,787,090 A (NEWMAN et al) 22 November 1988 (22.11.1988), col. 4 lines 47-68.	6, 7
Y	US 4,363,126 A (CHENAUSKY et al) 07 December 1982 (07.12.1982), Figs. 2, 5 and col. 1, line 47 - col. 3, line 47.	8-22

☐ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

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